



This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

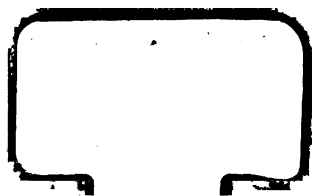
Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

- + *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.
- + *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.
- + *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.
- + *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

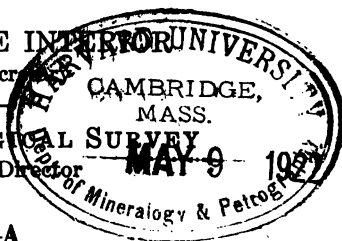
About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at <http://books.google.com/>



DEPARTMENT OF THE INTERIOR
ALBERT B. FALL, Secretary
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, Director

Bulletin 730—A



PENEPLAINS OF THE FRONT RANGE AND ROCKY MOUNTAIN NATIONAL PARK, COLORADO

BY

WILLIS T. LEE

Contributions to the geography of the United States, 1922

(Pages 1-17)

Published April 4, 1922



WASHINGTON
GOVERNMENT PRINTING OFFICE
1922

CONTENTS.

	Page.
Purpose of the paper.....	1
Two cycles of erosion previously recognized.....	1
A possible third cycle.....	2
Cycles of erosion in the Rocky Mountain National Park.....	4
Flattop cycle.....	4
Rocky Mountain peneplain.....	5
Canyon cycle.....	5
Correlation with peneplains of other areas.....	14
Physiographic history.....	14
First mountain uplift and early erosion.....	14
Flattop peneplain.....	15
Rocky Mountain cycle.....	15
Canyon cycle.....	16
Summary.....	17

ILLUSTRATIONS.

	Page.
PLATE I. Map and profile section of a part of the Central City quadrangle, Colo.....	2
II. A, Flattop Mountain, Colo., the type area of the Flattop peneplain; B, General view northwestward from Flattop Mountain.....	6
III. A, The Continental Divide, Colo.; B, Hallett Glacier, Colo.; C, Estes Park, Colo.....	7
IV. A, Thompson Canyon, Colo.; B, Gorge below Tyndall Glacier, Colo.....	8
V. A, Andrews Glacier, Colo.; B, Mills moraine, Colo.....	9
VI. A, The Chasm, Longs Peak, Colo.; B, Cirque near Comanche Peak, Colo.....	10
VII. A, Moraine south of Copeland Lake, Colo.; B, A timber-line tree on Longs Peak, Colo.....	11
VIII. A, Black Canyon and The Needles, Colo.; B, Longs Peak and Tahosa Valley, Colo.....	12
FIGURE 1. East-west profile across the Rocky Mountains through Longs Peak and Grand Lake, Colo.....	3
2. Profile across the Front Range through Flattop Mountain from Grand River to The Craggs, Colo.....	5
3. Profile from the crest of the mountains at Hagues Peak north-eastward to the Great Plains in northern Colorado.....	16

NOTE.—The Geological Survey's annual volumes entitled "Contributions to the geography of the United States" are issued in parts, and the last part will include a volume title-page, table of contents, and index for the use of those who may wish to bind the separate parts. A small edition of the bound volume will also be issued, but copies can not be supplied to those who have received all the parts.

CONTRIBUTIONS TO THE GEOGRAPHY OF THE UNITED STATES, 1922.

PENEPLAINS OF THE FRONT RANGE AND ROCKY MOUNTAIN NATIONAL PARK, COLORADO.

By WILLIS T. LEE.

PURPOSE OF THE PAPER.

The purpose of this paper is to call attention to some of the major surface features in the Rocky Mountain National Park, and to point out their probable correlation with similar features in neighboring regions. The observations on which the paper is based were made in the summer of 1916, during an investigation in which other work demanded first consideration. This paper may therefore be considered a by-product. For the same reason many of the observations were not followed to conclusions, yet the data obtained seem to be sufficient to establish a certain order of events, the recognition of which may be of assistance in working out in detail the geologic and geographic history of the Rocky Mountain region.

TWO CYCLES OF EROSION PREVIOUSLY RECOGNIZED.

In an account of the general geology of the Georgetown quadrangle, Colo., Ball¹ describes three distinct types of land forms—"an old, mature mountainous upland; younger V-shaped valleys incised in this upland; and glacial cirques developed at the heads of some of the streams, passing downward into U-shaped valleys." Ball describes the mountainous upland as consisting of highlands of rounded or gently sloping tops which are remnants of an ancient peneplain or old surface of erosion. Most of these remnants in the Georgetown quadrangle lie above an altitude of 11,500 feet. On this old peneplain there were many monadnocks, some of which are now recognizable as the summits of the highest mountains. Similar surfaces of erosion occur elsewhere in the mountains, among them the well-known upland plain near Pikes Peak, recognized by Cross.²

¹ Spurr, J. E., and others, *Economic geology of the Georgetown quadrangle (together with the Empire district)*, Colo. [General geology, by S. H. Ball]; U. S. Geol. Survey Prof. Paper 63, p. 31, 1906.

² Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Pikes Peak folio (No. 7), 1894.

Later Davis³ accepted Ball's description and applied to the highlands the term "a two-cycle mountain mass." This term and other expressions in his paper indicate that Davis believes that only two main cycles of erosion are represented in the Rocky Mountains in Colorado—an older one resulting in the formation of a peneplain and a younger one during which the canyons and cirques were excavated. Hence the remnants of the highland plain found at many places in these mountains are referred to as parts of "the peneplain."

A POSSIBLE THIRD CYCLE.

The dissected plateau near Pikes Peak which Cross described as practically the same as the floor of South Park was recognized by Richardson⁴ in the Castle Rock quadrangle and by Finlay⁵ in the Colorado Springs quadrangle. This plateau lies at altitudes between 9,000 and 9,500 feet and is extensively developed in the Front Range in Colorado. From localities at some distance from the mountains this plain appears to be an almost horizontal shelf that extends along the mountain front as far as the eye can reach. The area in which it is best developed and best preserved extends from Denver southward to Pikes Peak. In areas farther north, such as the mountains west of Golden, it is not so readily recognized, but it seems to be represented by surfaces much lower than the highland plain described by Ball as lying above 11,500 feet. Remnants of the lower plain may be recognized from some commanding eminence, such as Mount Lookout, near Golden, Colo., whose summit appears to be a part of the lower peneplain. This plain has become known somewhat widely as the Rocky Mountain peneplain, possibly because it is the most extensive land form in the Front Range. From Mount Lookout may be seen at nearly the same level numerous flat tops, benches, and smooth-floored reentrants (see Pl. I), which are remnants of the Rocky Mountain peneplain. But the best-known view of this peneplain is that which may be had from the side of Pikes Peak at an altitude of about 10,000 feet. From this point the observer looks to the north and west over the tops of the mountain ridges as over a level plain.

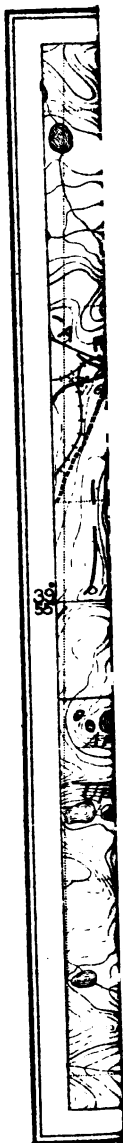
The reentrants seem to furnish indubitable proof of a distinct cycle of erosion. The older peneplaned surface was elevated, tilted, and dissected; the plain formed by the coalescing valleys has a slope notably different from that of the higher and older peneplain. A reentrant, possibly modified to some extent by glaciers, seen near Jenny Lake, Colo. (Pl. I), is a part of this new plain. This is one

³ Davis, W. M., *The Colorado Front Range: Assoc. Am. Geographers Annals*, vol. 1, p. 42, 1911.

⁴ Richardson, G. B., *U. S. Geol. Survey Geol. Atlas, Castle Rock folio (No. 198)*, 1915.

⁵ Finlay, G. I., *U. S. Geol. Survey Geol. Atlas, Colorado Springs folio (No. 203)*, 1916.

U. S.



FLATTOP

-11,000
-10,000
-9,000
8,000 FE

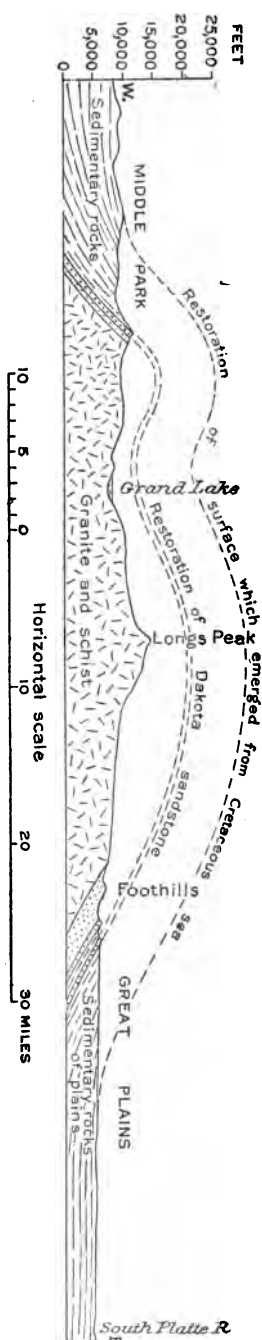
M

of the points of particular interest to tourists on the Denver & Salt Lake Railroad (Moffat road). This road winds over a surface of slight relief on the Rocky Mountain peneplain, enters the glacial cirque around Yankee Doodle Lake, and then ascends the steep slope leading to the high peneplain at Corona, which is described in this paper as the Flattop peneplain. Here a short walk brings the observer to the brink of the cliff, where he stands on the older peneplain, with the younger one in full view a thousand feet away.

Farther north there are old surfaces of considerable area, on which the rock is deeply disintegrated, such as that near Ward, at altitudes between 9,000 and 10,000 feet. These areas are parts of the Rocky Mountain peneplain. Still farther north, in the Rocky Mountain National Park, there are many remnants of a high plain, the Flattop peneplain, which corresponds to Ball's highland plain, and of a lower one, at an altitude of 10,000 feet or less (fig. 1), which corresponds to the Rocky Mountain peneplain. Both have been deeply dissected by the erosion of deep canyons during the present cycle.

Some geologists and geographers are disposed to regard the upland surfaces of both levels as parts of the same plain displaced by faulting; others see evidence here of two distinct peneplains which, together

FIGURE 1.—East-west profile across the Rocky Mountains through Longs Peak and Grand Lake, Colo. The Dakota sandstone marks the position of an ancient floor resulting from erosion, which base-leveled the site of the mountains. On this floor were deposited sediments of Cretaceous age. The mountain region was arched at the end of the Cretaceous period, and the sedimentary rocks were eroded. Records of early Tertiary events in the mountain region were destroyed by later erosion. The first definite Tertiary event is recorded in the Flattop peneplain, a remnant of which is shown on Longs Peak. An uplift rejuvenated the streams, and the Rocky Mountain peneplain was formed. This plain appears to correspond in general to the surface of the Great Plains and is believed to have been completed in late Tertiary time. Renewed uplift of the mountains, possibly at the beginning of Quaternary time, initiated the canyon cycle of erosion.



with the incised valleys and glacial cirques of the cycle not yet finished, make this a three-cycle rather than a two-cycle mountain mass.

CYCLES OF EROSION IN THE ROCKY MOUNTAIN NATIONAL PARK.

FLATTOP PENEPLAIN.

In the Rocky Mountain National Park near the crest of the highest range there are many flat or gently rounded surfaces that seem to be remnants of a peneplain. Most of them lie above timber line, which is here about 11,500 feet above the sea. One of the largest and most conspicuous of these remnants is on Flattop Mountain, whose name was suggested by its flat surface. (See Pl. II.) These remnants are so numerous and so close together that it is not difficult to reconstruct the old surface which they represent. Some of the gentler slopes are covered with residual soil, and the steeper ones with angular fragments of rock. A surface now connecting the several remnants would appear greatly warped and broken. Possibly the differences in altitude due to warping and faulting would in some places amount to a thousand feet or more. There are also peaks which were doubtless monadnocks on the old peneplain. Hallett Peak is plainly such a monadnock. (See Pl. II, A.) As viewed from the general level of the old peneplain this peak appears to be a dome rising about 500 feet, but from certain directions it appears to be a half dome, for the ancestor of Tyndall Glacier carried part of it away. Several smaller monadnocks are shown in Plate II, B. The nearly level top of Longs Peak may be a part of the Flattop peneplain warped up more than 2,000 feet, but it seems more likely that this mountain was a monadnock, although the nearly level surface of its summit, about 1,500 feet long and 1,000 feet wide, has been regarded as possibly a remnant of a peneplain still older than the Flattop peneplain. The rolling surface of the Flattop peneplain, which may be in part a product of recent warping, may be seen along the Continental Divide north of Longs Peak (Pl. III, A). Remnants of the same peneplain occur in many parts of the Rocky Mountain National Park on the highest mountains. Probably its most conspicuous remnant next to that on Flattop Mountain is on Hagues Peak (Pl. III, B).

In describing these highland surfaces as remnants of a peneplain I am not unmindful of the possibility that such surfaces may be formed in other ways,⁶ but here the large number of the remnants at about the same altitude and their wide distribution favor the belief in their formation by peneplanation.

⁶ Davis, W. M., *Leveling without base-leveling*: Science, vol. 21, pp. 825-828, 1905.

ROCKY MOUNTAIN PENEPLAIN.

On both sides of the high mountains the peaks rise to a fairly uniform altitude of about 10,000 feet. As viewed from a sufficient distance (see Pl. III) to obtain broad relations these peaks appear to stand at a general level 1,500 to 2,000 feet lower than the Flattop peneplain (see fig. 2), which seems to have resulted from a definite though uncompleted cycle of erosion. But the peneplain thus produced is not now rendered conspicuous by flat surfaces such as mark the higher peneplain, because of the intensive sub-aerial and subglacial erosion of a later cycle. Remnants of the older plain are preserved in spite of the long erosion that followed its uplift, because they lie near the heads of the streams and are affected but little by stream erosion.

This general level to which the mountains of intermediate height in the national park rise is here correlated with the Rocky Mountain peneplain, because it corresponds in position and apparently in age to the surface of the top of Mount Lookout.

CANYON CYCLE.

During the cycle of erosion not yet finished the Rocky Mountain peneplain has been deeply incised and throughout wide areas has been completely destroyed. This latest or canyon cycle is a composite one and will doubtless be subdivided when more detailed work is done, but for the present the preglacial canyon cutting and the ice action are grouped together under the name canyon cycle.

In the early part of this latest cycle the streams cut deep canyons, such as that of Thompson River (Pl. IV, A), through which the national park may be reached. Later in the cycle the heads of many of these canyons were glaciated and changed in form from the V-shape characteristic of stream work to the U-shape characteristic of glacial erosion. (See Pl. IV, B.)

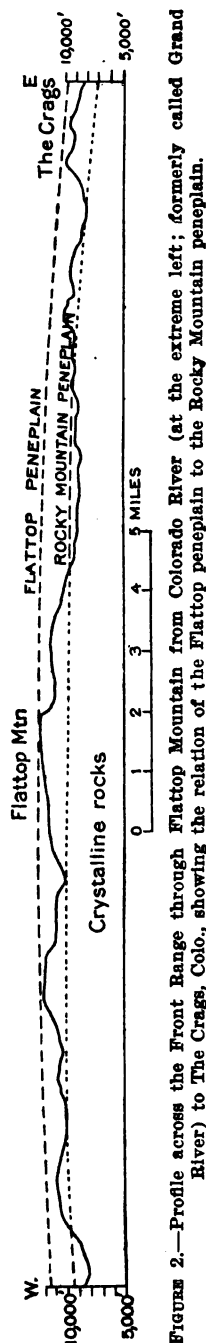


FIGURE 2.—Profile across the Front Range through Flattop Mountain from Colorado River (at the extreme left; formerly called Grand River) to The Crags, Colo., showing the relation of the Flattop peneplain to the Rocky Mountain peneplain.

PLATE II.

- A**, Flattop Mountain, the type area of the Flattop peneplain. The gently inclined surface is at an altitude of about 12,500 feet. In the distance to the left is the flat summit of Longs Peak; in the middle ground is the rounded summit of Hallett Peak, a monadnock rising from the old peneplain; and in the distance to the right are tilted remnants of the same plain. Photograph by F. W. Byerly.
- B**, General view from Flattop Mountain (altitude 12,500 feet) northwest and across the peneplain to the Medicine Bow Mountains, in the distance at the left, the peaks of which rise to about the level of Flattop.



A. FLATTOP MOUNTAIN, COLO.



B. GENERAL VIEW NORTHWESTWARD FROM FLATTOP MOUNTAIN.



A. THE CONTINENTAL DIVIDE, COLO.



B. HALLETT GLACIER, COLO.



C. ESTES PARK, COLO.

PLATE III.

- A**, View of the Continental Divide from Deer Mountain, showing the Flattop peneplain and two monadnocks, Hallett Peak and Taylor Peak, on the sky line. A remnant of the Rocky Mountain peneplain in the middle ground, the glacial gorge of Thompson River, and the west end of the lateral moraine lying south of Moraine Park.
- B**, Hallett Glacier and a part of the Flattop peneplain at an altitude of 13,400 feet, north of Hagues Peak. In the dark parts of the glacier old crevassed ice is exposed.
- C**, View from Prospect Mountain northwestward across Estes Park to The Needles, showing the Rocky Mountain peneplain and a remnant of the higher or Flattop peneplain on the distant sky line. The park was eroded about 2,500 feet below the Rocky Mountain peneplain and shaped probably by the ice of the older or pre-Wisconsin stage of glaciation.

79152°—22—2

7

PLATE IV.

- A, A** V-shaped valley of the canyon cycle of erosion in the lower end of Thompson Canyon, cut in the upturned quartzite; looking downstream toward the Great Plains. In the distance is the "Red Beds" hogback of the foothills east of the mountains.
- B, A** V-shaped valley or glacial gorge cut in granite and schist by ice during the canyon cycle of erosion. Tyndall Glacier, at the head of the gorge, extends up to the Flattop peneplain at an altitude of 12,300 feet. The lake in the foreground is at an altitude of 10,200 feet and is $1\frac{1}{4}$ miles from the head of the glacier. The cliffs rise about 2,000 feet above the lake.



A. THOMPSON CANYON, COLO.



B. GORGE BELOW TYNDALL GLACIER, COLO.



A. ANDREWS GLACIER, COLO.



B. MILLS MORaine, COLO.

PLATE V.

A, A view of Andrews Glacier from the lake in which the ice at its foot melts.
Because of the great bend in the center the upper half of the glacier is not seen from the lake.

B, Mills moraine, as seen from Twin Sisters. The glacier originated in The Chasm (Pl. VI, A), on the east slope of Longs Peak, and was about 4 miles long. The rock débris carried out of The Chasm was dropped chiefly at the sides, building up the ridges shown in the photograph. The moraines range in altitude from 9,500 feet at their base to nearly 12,000 feet.

PLATE VI.

CIRQUES FORMED DURING THE WISCONSIN STAGE OF GLACIATION.

- A*, The Chasm, in the eastern face of Longs Peak, as seen from Chasm Lake. The precipitous face of the cirque rises about 2,400 feet above the lake.
- B*, The cirque on the northern boundary of the Rocky Mountain National Park, 1 mile southwest of Comanche Peak, as seen from the saddle north of Hagues Peak, a distance of 5 miles. The cirque is 1 mile long, half a mile wide, and 1,000 feet deep. On both sides of the cirque is the Flattop peneplain, which has a maximum altitude here of more than 12,500 feet.



A. THE CHASM, LONGS PEAK, COLO.



B. CIRQUE NEAR COMANCHE PEAK, COLO.



A. MORaine SOUTH OF COPELAND LAKE, COLO.



B. A TIMBER-LINE TREE ON LONGS PEAK, COLO.

PLATE VII.

- A*, View from Copeland moraine above Copeland Lake, across the St. Vrain to the lateral moraine south of the valley. The glacier which built these great moraines originated in Wild Basin south of Longs Peak and moved down the valley 10 miles or more.
- B*, A timber-line tree (limber pine) on Longs Peak. A result of the prevailing westerly wind, which sweeps the snow from the highland plains into the cirques of the eastern slopes. The intense dissection of the mountains east of Continental Divide near Longs Peak (see topographic map of Longs Peak quadrangle) is due largely to glaciers formed of snow swept by the west wind from the Flattop peneplain.

PLATE VIII.

RESULTS OF PRE-WISCONSIN GLACIATION.

- A, Black Canyon and The Needles.** This canyon was not occupied by ice during the last stage of glaciation, but the broad, gently sloping floor and precipitous wall of granite rising 2,000 feet to the Rocky Mountain peneplain, which appears on the right, is suggestive of intensive ice action such as shaped the Yosemite Valley.
- B, Longs Peak and Tahosa Valley.** This valley is outside the area of Wisconsin glaciation, but its broad, smooth floor at an altitude of 9,000 feet, a mile or more in width, with mountains east of it rising to an altitude of 11,436 feet within a mile and mountains west of it rising to an altitude of 14,255 feet within 4 miles, suggests glacial action.



A. BLACK CANYON AND THE NEEDLES, COLO.



B. LONGS PEAK AND TAHOSA VALLEY, COLO.

At least two stages of glaciation are represented here—a later one, presumably corresponding in time to the Wisconsin stage, and an earlier one, corresponding in time to one of the older recognized stages. The results of the latest glaciation are conspicuously exhibited in the national park. Deep gorges (Pl. IV, *B*) and cirques were scooped out of the mountain sides by the ice, and morainal matter was heaped up to a depth of 1,000 feet or more. Many if not all of the gorges and cirques are stream-cut valleys that have been modified in form by the ice, but the excavation in some of them, such as The Chasm, on Longs Peak (Pl. V, *B*), was chiefly the work of a glacier, a fact shown by a comparison of the size of the cirque with the volume of morainal matter which obviously came from it. The ice at the Wisconsin stage modified the topography of both the Flattop peneplain and the Rocky Mountain peneplain. The gorge below Tyndall Glacier (Pl. IV, *B*) is cut into the higher plain, as is also the remarkably fine cirque near Comanche Peak (Pl. VI, *B*). The Rocky Mountain peneplain was affected to a less extent by the ice, for at the time it existed the glaciers on the eastern slope of the mountains occupied only the bottom parts of the valleys (Pl. III, *A*). Some of the moraines, such as the Mills moraine, were formed in part above the level of the Rocky Mountain peneplain (Pl. V, *B*), but most of them were built at lower levels (Pls. III, *A*, and VII, *B*).

Some of the cirques and gorges still contain large bodies of snow and ice. It is uncertain how many of these bodies should be called glaciers. The mass of ice on Hagues Peak (Pl. III, *B*) has been named Hallett Glacier, after Mr. W. L. Hallett, of Colorado Springs, who visited it in 1884 and noted the crevasses in the ice. For many years it was generally supposed that the Hallett was the only true glacier in the Longs Peak region, but now four other bodies of ice in this group of mountains are recognized as glaciers and named on the topographic map of the Longs Peak quadrangle—Sprague Glacier, an arm of which is shown in Plate II, *A*; Tyndall Glacier, shown in the distance in Plate IV, *B*; Andrews Glacier, the body of ice shown in Plate V, *A*; and Taylor Glacier.

The former presence in the Longs Peak region of glaciers older than those of the Wisconsin stage has not been demonstrated, but such features as U-shaped valleys, perched lakes, and peat-filled basins beyond the known limits of the Wisconsin ice go far toward such a demonstration. In the Black Canyon (Pl. VIII, *A*) the broad floor of the valley and the steep cliffs that rise precipitously 2,000 feet at its side suggest oversteepening of the walls by ice. In the character of the rock of the walls, which is massive granite, and in the form of the valley there is so striking a resemblance to Yosemite Valley as to suggest similar origin, yet Black Canyon did not contain a glacier during the Wisconsin stage. It is tributary

to Estes Park (Pl. III, *C*), which presumably was filled with ice during this older stage of glaciation. Tahosa Valley (Pl. VIII, *B*) also may have been shaped, at least in part, by the older glaciers.

CORRELATION WITH PENEPLAINS OF OTHER AREAS.

The Flattop peneplain is probably to be correlated with the highland plain of the Georgetown quadrangle described by Ball. The canyon cycle is obviously the same everywhere along the Front Range, for the canyons are all of essentially the same degree of development. The intermediate cycle was not definitely recognized by Ball, and it is not easily discernible in the Georgetown quadrangle. However, from Golden southward to the Pikes Peak region the peneplain formed during the intermediate cycle appears as the great conspicuous upland called in this paper the Rocky Mountain peneplain.

A question has been raised as to the meaning of the intermediate highlands. There is little doubt that faulting and warping of relatively recent date has occurred in many parts of the mountains, and some of the surfaces here interpreted as remnants of the Rocky Mountain peneplain may possibly be displaced parts of the higher plain let down by faulting; but it is scarcely probable that the intermediate cycle of erosion can be explained away in this manner. Although my observations were hurried and limited to a small area I am disposed to believe that the Front Range is a three-cycle rather than a two-cycle mountain mass.

PHYSIOGRAPHIC HISTORY.

Although the physiographic history of the Rocky Mountains is imperfectly known, a probable chronologic order of events can be worked out which may be of value, at least in stimulating observation. A partial list of events, given in order from oldest to youngest, follows.

FIRST MOUNTAIN UPLIFT AND EARLY EROSION.

Reasons for believing that sedimentary deposits of Cretaceous age covered the site of the mountains in Colorado and that the mountains emerged from the sea at the end of the Cretaceous period have been given in an earlier publication.⁷ As that publication is easily available these reasons need not be repeated here.

After the initial uplift the sedimentary rocks were eroded, at least in part, from the area later carved into mountains. Also during this early period of erosion andesite⁸ was extruded in the mountain region, and this also was eroded away and waste from it was included in the early Tertiary beds (Denver formation).

⁷ Lee, W. T., Relation of the Cretaceous formations to the Rocky Mountains in Colorado and New Mexico: U. S. Geol. Survey Prof. Paper 95, pp. 27-56, 1916.

⁸ Cross, Whitman, Geology of the Denver Basin in Colorado: U. S. Geol. Survey Mon. 27, p. 315, 1896.

FLATTOP CYCLE.

Perhaps somewhat later, although this can not be asserted with confidence, flows of rhyolite and andesite were formed in the region north of Longs Peak. These flows were later broken up, and the blocks were transported, presumably by water, to the lowlands or broad valleys of that time, which had been eroded in the crystalline rocks of the mountain core. Here the *débris* of rhyolite and andesite was interbedded with volcanic ash, tuff, and flows of glassy lava, the composite mass occupying a wide area and resting on a floor of old crystalline rock. With the blocks of rhyolite were embedded rounded pebbles and boulders of granite, gneiss, and schist so large as to indicate that highlands of crystalline rock of considerable altitude existed near by at that time. A large mass of this composite material many hundreds of feet thick is preserved in Specimen Mountain, in the northern part of the Rocky Mountain National Park. As the base of the material is at nearly the same altitude as the Flattop peneplain, it may be that the broad valleys in which the material accumulated were due to erosion in the early part of the cycle which produced the Flattop peneplain and that the highlands which furnished the boulders of crystalline rock are represented now by such old monadnocks as Hallett Peak.

The formation of the Flattop peneplain was the third major event in the history of this region. Apparently the mountain region was elevated 2,000 feet or more, and the consequent erosion reduced the greater part of it nearly to a plain, leaving many monadnocks, such as Hallett Peak (Pl. III, A), Longs Peak, and Mount Evans. The bedded deposits of rhyolite and andesite *débris* which accumulated in the cycle were partly eroded away, and dikes of the same material were planed off even with the general surface. One large mass, that of Specimen Mountain, escaped erosion.

There is little evidence by which the date of this peneplain can be fixed, but the general succession of events indicates the improbability that it was formed before the end of the Eocene epoch, and the equal improbability that it is later than Pliocene.

ROCKY MOUNTAIN CYCLE.

Renewed uplift still further arched the great mountain anticline, lifting the center 1,500 to 2,000 feet. This uplift rejuvenated the streams, and the Rocky Mountain peneplain was formed. This is probably the most extensive physical feature of the mountain region in northern Colorado. Its formation required a long time. Many facts point to its being the mountain equivalent of the Great Plains, as is suggested by such profiles as those in Plate IV of the Denver

Basin monograph,⁹ those of the Castle Rock folio,¹⁰ and those of

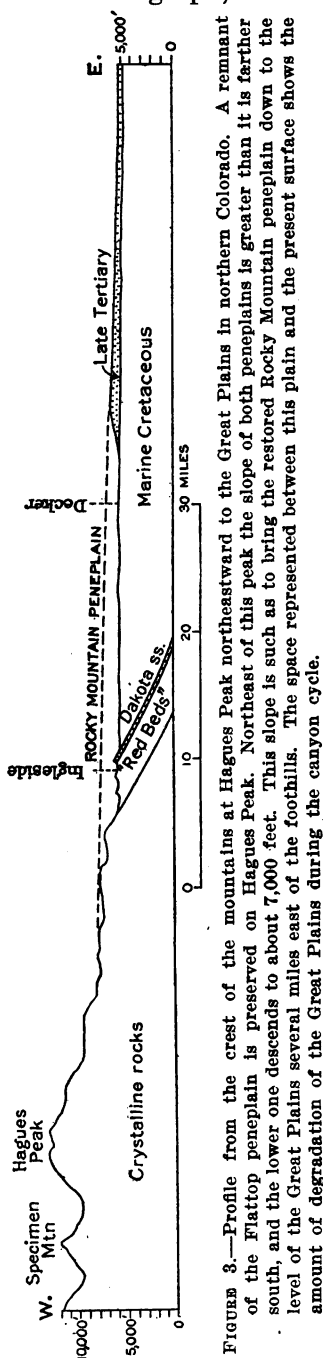


FIGURE 3.—Profile from the crest of the mountains at Hagues Peak northeastward to the Great Plains in northern Colorado. A remnant of the Flat-top peneplain is preserved on Hagues Peak. Northeast of this peak the slope of the peneplain is greater than it is farther south, and the lower one descends to about 7,000 feet. This slope is such as to bring the restored Rocky Mountain peneplain down to the level of the Great Plains several miles east of the foothills. The space represented between this plain and the present surface shows the amount of degradation of the Great Plains during the canyon cycle.

figure 3 of this paper. Doubtless the erosion that produced this peneplain furnished the material for the beds of late Tertiary age east of the mountains.

Certain gravel beds observed near the tops of the mountains between Palmer Lake and Florissant may be due to the activity of some of the streams that helped to form this peneplain. These were observed many years ago by George H. Stone, who published in the Colorado Springs Gazette in 1900 a sketch map showing a large body of gravel on the highlands east of Florissant, near Divide station on the Colorado Midland Railway, between the headwaters of South Platte River and Fountain Creek. Smaller bodies of gravel which seem to mark the course of an old river lie between this locality and Palmer Lake. On Stone's map the site of the large body of gravel was called Hayden Lake, and the line of gravel beds between this body and Palmer Lake was called Hayden River. These gravel beds suggest the headwaters of one of the streams which in late Tertiary time furnished the pebbles of the gravel beds that still cover vast areas of the Great Plains in eastern Colorado.

CANYON CYCLE.

The Rocky Mountain cycle of erosion was terminated by renewed uplift accompanied by much warping of the surface and great displacement by faulting in many localities. South of Denver the Rocky Mountain peneplain seems to have been lifted without notable warping, the displacement being generally accomplished by slipping along fault planes in the foothill region. In north-

⁹ Emmons, S. F., and others, *Geology of the Denver Basin*, in *Colorado: U. S. Geol. Survey Mon.* 27, 1896.

¹⁰ Richardson, G. B., *U. S. Geol. Survey Geol. Atlas, Castle Rock folio (No. 198)*, 1915.

ern Colorado the uplift seems to have partaken more of the nature of arching (see fig. 3), so that the older plain on Hagues Peak is about 5,000 feet higher than the younger plain in the foot-hill region.

(There are some reasons for believing that this orographic disturbance marks the beginning of the Quaternary period. The surface gravel of the plain, which seems to have been spread out by streams in the later part of the Rocky Mountain cycle, contains fossil bones said to indicate Pliocene or Pleistocene time. If this dating of the last great uplift of the Rocky Mountains at the beginning of the Quaternary is correct, the canyon cycle of erosion is coextensive with Quaternary time.) The work of cutting these canyons is comparable to that in the San Juan River region, where canyons 2,000 feet deep have been cut since the oldest Pleistocene glaciation of that region.¹¹ The dissection and degradation of the Great Plains near the mountains accomplished during the canyon cycle is no greater than the degradation in Montana since the early glaciation, now represented by the till which caps certain mesas having a maximum height of about 1,000 feet above the surrounding country.¹²

SUMMARY.

There is fairly satisfactory evidence in the Rocky Mountain National Park of three distinct cycles of erosion—one which resulted in the Flattop peneplain and was completed some time near the middle of the Tertiary period; one which resulted in the Rocky Mountain peneplain and was probably terminated at the end of the Tertiary; and the canyon cycle, not yet completed. A peneplain still older than the Flattop peneplain may be represented by the top of Longs Peak and other high mountains in Colorado, many of which have nearly the same altitude.

¹¹ Atwood, W. W., and Mather, K. F., The evidence of three distinct glacial epochs in the Pleistocene history of the San Juan Mountains, Colo.: Jour. Geology, vol. 20, p. 401, 1912.

¹² Alden, W. C., and Stebinger, Eugene, Pre-Wisconsin glacial drift in the region of Glacier National Park, Mont.: Geol. Soc. America Bull., vol. 24, pp. 529-572, 1913.



DEPARTMENT OF THE INTERIOR

ALBERT B. FALL, Secretary

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, Director

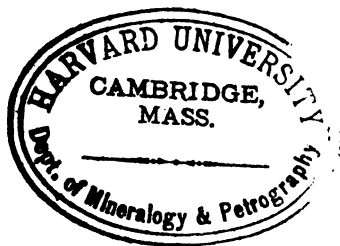
Bulletin 730—B

EROSION AND SEDIMENTATION IN THE
PAPAGO COUNTRY, ARIZONA

WITH A SKETCH OF THE GEOLOGY

BY

KIRK BRYAN



Contributions to the geography of the United States, 1922

(Pages 19-90)

Published June 8, 1922



WASHINGTON

GOVERNMENT PRINTING OFFICE

1922

CONTENTS.

	Page.
Introduction.....	19
Geology.....	20
Stratigraphy.....	20
Pre-Cambrian basal complex.....	21
Paleozoic rocks.....	22
Mesozoic rocks.....	24
Sedimentary rocks.....	24
Igneous rocks.....	25
Tertiary rocks.....	26
Sedimentary rocks.....	26
Volcanic rocks.....	26
Quaternary deposits.....	28
Alluvial materials.....	28
General character.....	28
Older alluvium.....	29
Younger alluvium.....	30
Recent deposits.....	32
Basalt.....	32
Structure.....	33
Faulting.....	33
Faults in the Sand Tank Mountains.....	34
Faults in the Tule Mountains.....	35
Faults in the Growler Mountains.....	36
General character of the mountains.....	36
Physiography.....	37
Influence of aridity.....	37
Mountain sculpture.....	38
Mountain slopes.....	38
Conditions determining mountain slopes.....	38
Mechanical processes of erosion.....	39
Chemical processes of erosion.....	41
Grades of mountain slopes.....	42
Cliffy slopes.....	42
Boulder-controlled slopes.....	43
Rain-washed slopes.....	46
Canyon cutting.....	46
Headwater basins.....	48
Minor erosional features.....	49
Mountain pediments.....	52
Character.....	52
Origin.....	54
Concealed pediments.....	58
Coalescing pediments.....	60
Dissected pediments.....	60
Cause of dissected pediments in the Papago country.....	63

Physiography—Continued.	Page.
Valleys	65
Structural origin of valleys.....	65
Processes of change operating in the valleys.....	66
Features of the valley floors.....	66
Drainage.....	66
Axial streams.....	67
Tributary streams.....	68
Adobe flats.....	69
Playas.....	70
Wind deposits.....	70
Terraces.....	71
Terraces of Gila River.....	71
Terraces of Altar and Santa Cruz valleys.....	73
Terraces in the interior valleys.....	80
Geologic and physiographic history.....	81
Pre-Tertiary episodes.....	81
Tertiary landscape.....	82
Pleistocene and Recent time.....	83
Glossary	86

ILLUSTRATIONS.

	Page.
PLATE IX. Reconnaissance geologic map of the Papago country, Ariz. In pocket.	
X. A, Ajo Peaks, Ariz., from the east; B, Clifly slopes of massive lava flows on the west side of the Ajo Mountains, Ariz.....	42
XI. A, Growler Mountains south of Bates Well, Ariz., from the west; B, Lava-capped mountain in the Cabeza Prieta Mountains, Ariz., from the west.....	43
XII. A, Pass west of Tule Tank, Ariz.; B, Mountain slope and dissected pediment.....	60
XIII. A, Headwater basin and dissected pediment in the Sand Tank Mountains, Ariz.; B, East slope of Maricopa Mountains, Ariz.....	61
FIGURE 4. Geologic cross sections in the western part of the Sand Tank Mountains, Ariz.....	34
5. Geologic cross section in the Tule Mountains, Ariz.....	35
6. Geologic cross section of the southern part of the Lechuguilla Desert, Ariz.....	35
7. Diagram to show the range of mountain slopes.....	42
8. Sketch map of the Papago country, Ariz., showing distribution, so far as observed, of gullied and ungullied mountains of approximately the same size.....	44
9. Diagram showing three stages in the erosion of a block of the earth's crust to form the sierra type of mountain.....	47
10. Cross section of niche in granite at Tinajas Altas, Ariz.....	49
11. Diagram illustrating weathering of Tertiary arkose conglomerate in the Papago Saguaro National Monument, Ariz.....	50

	Page.
FIGURE 12. Cross section of a niche in coarse conglomerate, Papago Saguaro National Monument, Ariz-----	51
13. Map of part of the Sacaton Mountains, Ariz-----	52
14. Map of the northern border of the Baboquivari Mountains, Ariz-----	53
15. Diagram showing the structural relations resulting from the slow but continuous filling of a structural basin-----	56
16. Diagram showing the structural relations resulting from the rapid and continuous filling of a structural basin-----	58
17. Diagram showing the structural relations resulting from the discontinuous filling of a structural basin-----	59
18. Sketch map of the northwestern part of the Sand Tank Mountains, Ariz., showing location of dissected and concealed pediments-----	60
19. Map of the vicinity of Fresnal and Topahua, Ariz., showing dissected pediment-----	62
20. Diagram showing the structural relations assumed for a typical valley in the Papago country, Ariz-----	63
21. Cross sections on the north and west sides of the Baboquivari Mountains, Ariz-----	64
22. Cross section of part of Santa Cruz Valley (Nogales Wash), Ariz., from Mount Benedict to the Tumacacori Mountains--	74
23. Cross section of Santa Cruz Valley from Sardina Peak to the Santa Rita Mountains near Tubac, Ariz-----	75
24. Cross section of Santa Cruz Valley at Jaynes, Ariz-----	75
25. Cross section of Santa Cruz Valley near Toltec, Ariz-----	76

EROSION AND SEDIMENTATION IN THE PAPAGO COUNTRY, ARIZONA,

WITH A SKETCH OF THE GEOLOGY.

By KIRK BRYAN.

INTRODUCTION.

The Papago country, as the term is used in this paper, is a region of about 13,000 square miles in southwestern Arizona. As shown on Plate IX (in pocket), it is bounded on the north by Gila River, on the east and west by Santa Cruz and Colorado rivers, respectively, and on the south by the boundary between the United States and Mexico. It is a part of the vast region of northern Sonora and southern Arizona which was known to the early Spanish explorers as the Pimería Alta, but which later, when the Spaniards came to distinguish the Papagos or nomadic agriculturists of this region from the more sedentary Sobaipuris and Pimas of the Santa Cruz and Gila valleys, they called the Papaguera.

The mean annual rainfall of the Papago country ranges from $3\frac{1}{2}$ to 11 inches. The mean annual temperature at Tucson is 67° F. and at Yuma 72° F. The mean temperature at Ajo in 1919 was 70° F. The small rainfall and high temperature with consequent excessive evaporation combine to make the region one of the driest parts of the United States, and much of it is, in fact, true desert. The climatic conditions have produced a striking assemblage of plants, in which large cacti, numerous trees, and woody shrubs are characteristic.¹ This arboreal desert has a deceiving verdure that is in great contrast to the scarcity of watering places.

The broad expanse of desert has a characteristic topography. Small and large groups of mountains are separated by broad basins or valleys. The mountains are so arranged that the valleys have a general north-south trend, but the parallelism of the ranges is by no means so complete as indicated on earlier maps. From the southeast corner, near Nogales, where the valleys have elevations that range from 3,200 to 3,500 feet, there is a general slope to the north

¹ MacDougal, D. T., Botanical features of North American deserts: Carnegie Inst. Washington Pub. 99, 1908. Spaulding, V. M., Distribution and movements of desert plants: Carnegie Inst. Washington Pub. 113, 1909. Mearns, E. A., Mammals of the Mexican boundary of the United States, part 1: U. S. Nat. Mus. Bull. 56, 1907.

and west, each valley to the west being lower than that to the east, until on the western edge of the region the Yuma Desert, bordering Colorado River, has a general elevation of 250 feet.

The field work of which the present paper is a by-product was begun September 4 and continued to December 23, 1917. The primary object of the investigation was to prepare a guide to the desert watering places of the Papago country.

To the intelligent and observing traveler the surface features of a desert region like the Papago country are a constant source of enjoyment and interest. The bold slopes of the mountains, brown and desolate if composed of schist or gneiss, variegated, cliffed, and pinnacled if composed of thick and massive lava flows, present a remarkable contrast to the generally smooth and verdant slopes of mountains in more humid lands. The broad plains which support orchardlike forests of strange trees and cultivated fields yet contain no watering places impress him with the majesty and mystery of the desert. These land forms, interesting in themselves and exercising complete control over the lives of the Papagos and the movements of travelers, are the result in large part of processes peculiar to a desert region. The object of this paper is to describe these land forms and to discuss their probable mode of origin. The rock framework is briefly described in a sketch of the geology of the region in order to form a setting for a discussion of processes that have been active in the production of the desert landscape.

The investigation was conducted under the direction of O. E. Meinzer, geologist in charge of the division of ground water, and to him the author is indebted for a free hand in developing the problems discovered in the course of the work. C. P. Ross, who conducted a similar investigation north of Gila River, has cooperated harmoniously along an extensive boundary line. C. G. Puffer, field assistant, contributed largely to the success of the work by his ability to make desert travel easy if not luxurious. The writer is indebted for generous criticism to Dr. H. H. Robinson and Prof. Chester R. Longwell. M. R. Campbell and other members of the physiographic committee of the United States Geological Survey have been most helpful in the critical reading of the text.

GEOLOGY.

STRATIGRAPHY.

The rocks of the Papago country consist of pre-Cambrian schist, gneisses, and intrusive rocks, Paleozoic limestones and quartzites,

¹ Bryan, Kirk, Routes to desert watering places in the Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 490-D, 1922; The Papago country, a geographic, geologic, and hydrologic reconnaissance: U. S. Geol. Survey Water-Supply Paper — (in preparation; contains detailed descriptions of the mountains and valleys).

Mesozoic clastic rocks and granitic intrusives, Tertiary conglomerates and volcanic rocks, and Quaternary alluvium.

The pre-Cambrian rocks are a basal complex whose history is as yet unraveled and which is separated by a great unconformity from the succeeding rocks. The Paleozoic rocks now exist as scattered patches infaulted into the pre-Cambrian or embedded in later Mesozoic intrusive rocks. The Mesozoic clastic rocks are arkosic sandstones and shales, which are separated from the Paleozoic limestones and quartzites by an unconformity. The Mesozoic igneous rocks occupy large areas, but the granitic intrusives and more or less metamorphosed lava flows are not easily distinguished from the pre-Cambrian, and the undifferentiated rocks of both ages are referred to as the crystalline complex. The Tertiary conglomerates and lava flows are separated from all the rocks previously formed by an unconformity that represents a desert surface in the old age of erosion. The pre-Tertiary and Tertiary rocks form the mountains and hills, but in the valleys lies a great mantle of alluvium, composed of débris derived from the destruction of the older formations. The general distribution of these rocks is shown on the geologic map (Pl. IX) and is more particularly described below.

PRE-CAMBRIAN BASAL COMPLEX.

The pre-Cambrian rocks of the region form a highly metamorphosed complex consisting largely of schists and gneisses. No sequence of pre-Cambrian sedimentary rocks such as have been found north of Gila River³ has yet been determined, but doubtless some of the schists and gneisses are metamorphosed sedimentary rocks. In the northern part of the Salt River Mountains the complex is mostly chloritic schist. In the Sand Tank Mountains chloritic schists have been feldspathized, and there are many transitions from schist to gneiss. Fine-grained biotite granite and phyllite occur also. The northern parts of the Gila Mountains are composed mostly of coarse biotite granite and micaceous and hornblende schist and gneiss. As noted by Blake,⁴ near the Fortuna mine the schistosity dips 45° to the south and west and is very even and regular. There hornblende schist predominates, and parallel to the schistosity are quartzose beds in which gold occurs. Blake noted also feldspathic dikes that intersect the schistosity and seem to be connected with great intrusions of pinkish granite, which form the higher peaks.

The older gneisses, which are of pre-Cambrian age, in many localities have a very definite sheeting that divides them into layers from

³ Ross, C. P., *Geology of the lower Gila River region, Ariz.*: U. S. Geol. Survey Prof. Paper 129, pp. 153-181, 1922.

⁴ Blake, W. P., *Geology of the Gila Range*: Governor of Arizona Rept., 1898, p. 25.

2 to 4 feet thick. Such gneisses, which are easily distinguished from the later intrusive rocks of supposed Mesozoic age, were observed near Tule Tank, in the Cabeza Prieta Range, and in the Baker Peaks, Sierra Blanca, and Coyote Mountains. In the Coyote Mountains the almost perfect sheeting controls the erosion of the mountain, which has the topographic form of a monoclinal block of sedimentary rock.

PALEOZOIC ROCKS.

The Paleozoic rocks occur in two situations—as plates or blocks resting on the eroded surface of the pre-Cambrian complex, or as blocks more or less engulfed and metamorphosed by later intrusions.

In the western part of the Tucson Mountains, beneath a blanket of lava, mostly Tertiary rhyolite,⁵ lie limestone and quartzite of Cambrian and Carboniferous age.⁶ At Snyders Hill, just west of Robles Pass, blue limestone has been quarried for burning lime, and also for road metal. Fossils collected at this locality have been identified by G. H. Girty as follows:

Zaphrentis? sp.

Pustula aff. *P. porrecta*.

Productus aff. *P. subhorridus*.

Rhynchopora? n. sp.

Squamularia perplexa.

Composita mexicana.

Mr. Girty considers that this fauna is probably younger than that found at the Vekol mine and indicates upper Pennsylvanian, perhaps even Permian time.

South of this locality, on the east side of the Sierrita Mountains, limestones and shales, partly metamorphosed and containing copper, occur at Mineral Hill and Twin Butte.⁷

The ore deposits of Silver Bell occur in blocks of limestone embedded in post-Paleozoic intrusive rocks.⁸ In the near-by Silver Bell Mountains Tolman⁹ found 3,700 feet of alternating quartzite, shaly quartzite, and limestone, of which the massive limestone contains Carboniferous fossils.

North of Pozo Blanco, at the east foot of the Sierra Blanca, the galena ore of the Black Prince mine is found in blocks of blue lime-

⁵ Tolman, C. F., The geology of the vicinity of the Tumamoc Hills: Carnegie Inst. Washington Pub. 113, p. 76, 1909.

⁶ Blake, W. P., Geologic sketch of the region of Tucson, Ariz.: Carnegie Inst. Washington Pub. 99, pp. 45-68, 1908. Jenkins, O. P., and Wilson, E. D., A geological reconnaissance of the Tucson and Amole mountains: Arizona Univ. Bur. Mines Bull., Geol. Ser., No. 2, p. 11, 1920.

⁷ Blake, W. P., op. cit., p. 53.

⁸ Stewart, C. A., The geology and ore deposits of the Silver Bell mining district, Ariz.: Am. Inst. Min. Eng. Trans., vol. 43, pp. 240-290, 1913.

⁹ Tolman, C. F., Copper deposits of Silverbell, Ariz.: Min. and Sci. Press, vol. 99, pp. 710-712, 1909.

stone which, with some red shale, are embedded in intrusive rocks. No fossils were found at this locality.

The northern part of the Vekol Mountains consists of a monocline of limestone, quartzite, and shale, extending from the Vekol mine to the Reward mine. These sedimentary rocks rest on a basal complex of schist, granite, and diorite and have been faulted and intruded by granitic masses and later siliceous porphyry dikes and plugs.¹⁰ On the south side of the monocline, near the Vekol mine, fossils were collected in three lots from a thickness of about 200 feet of thick-bedded gray limestone. The surface of this limestone is marked by brown siliceous concretions, and the lower beds are cherty. Near the mine the same limestone is red. The fossils were submitted to G. H. Girty, who reports the following combined list:

Cladochonus sp.
Campophyllum torquium.
Rhombopora lepidodendroides.
Schizophoria? sp.
Chonetes verneuillianus.
Productus semireticulatus.
Marginifera splendens.
Spirifer cameratus.
Spirifer rockymontanus.
Composita subtilita.

Mr. Girty states that the beds are "Pennsylvanian, apparently lower Pennsylvanian." They thus correspond in age to the lower part of the Naco limestone of the Bisbee district.¹¹

About 14 miles northwest of the Vekol mine and 3 miles east of Stouts Well is a small hill composed of massive gray limestone, which dips gently to the southeast. About 100 feet of limestone is exposed. This mass appears to be an unfaulted fragment of the great limestone series exposed in the Vekol Mountains. A few fossils were collected and submitted to Edwin Kirk, who reports as follows:

There are no determinable fossils in the lot that definitely fix the stratigraphic horizon. The crinoid fragments, however, are of such a nature that they could not be older than Devonian nor younger than Carboniferous. There is little doubt in my mind that the material is of Carboniferous age.

West of this hill only one other outcrop of limestone was found. At the east side of Growler Pass is a high, irregular hill composed of limestone and quartzite which appear to have been mashed and the limestones later silicified. Because of this alteration fossils seem to be rare, and none were found by the writer in the short time available.

The remnants of Paleozoic rocks occurring at widely scattered places in the Papago country indicate that the Paleozoic seas were

¹⁰ Higgins, Edwin, Vekol copper deposits (Pinal County, Ariz.): Eng. and Min. Jour., vol. 91, pp. 473-474, 1911.

¹¹ Ransome, F. L., Some Paleozoic sections in Arizona and their correlation: U. S. Geol. Survey Prof. Paper 98, p. 148, 1916.

limited on the west by land. The Cambrian and Devonian rocks extend no farther west than the Santa Rita and Tucson mountains; the later Paleozoic (Pennsylvanian) has a wider extent. Earth movements following the Paleozoic era, with consequent erosion, contributed the clastic materials that now form the Mesozoic sedimentary rocks and destroyed a large part of the previously deposited Paleozoic rocks. Similarly uplift and subsequent erosion which were incident to the Mesozoic period of igneous activity further diminished the volume of Paleozoic rock, which now forms isolated blocks that are separated by great distances and are preserved largely because they are unfaulted and protected by other formations.

MESOZOIC ROCKS.

SEDIMENTARY ROCKS.

In the Santa Rita and Patagonia mountains, small portions of which are shown on the geologic map (Pl. IX), Schrader and Hill found a great series of shale, sandstone, and conglomerate, with calcareous layers, aggregating about 6,000 feet in thickness.¹² Fossils found in a thin-bedded arenaceous limestone near Mowry indicate, according to T. W. Stanton, that the beds are of Lower Cretaceous (Comanche) age. Because of faunal and lithologic similarities Schrader¹³ considers that the Mesozoic rocks of the Santa Rita and Patagonia mountains are equivalent to the Comanche series ("Bisbee group") of the Bisbee quadrangle.¹⁴ At Bisbee there are numerous beds of limestone with a well-developed marine fauna. In the Patagonia region, however, the calcareous layers are few, and the greater part of the beds are red sandstone and shale.

What seem to be the same rocks are found in the Tumacacori Mountains. Just east of the Montana mine is a great mass of red sandstone, conglomerate, and shale, dipping to the west at high angles and unconformably overlain by tuff. Both east and west of Arivaca are red and green shales with incipient slaty cleavage, which may be part of the same formation. Red sandy shale and arkosic gray sandstone of a total thickness of 2,140 feet, attributed to Mesozoic time, have been found in the Tucson Mountains.^{14a}

West of the Tumacacori Mountains red shale and arkose sandstone were seen at Agua la Vara, faulted against the gneiss of the Coyote Mountains, and again at Pozo Blanco associated with the limestone

¹² Schrader, F. C., and Hill, J. M., Mineral deposits of the Santa Rita and Patagonia mountains, Ariz.: U. S. Geol. Survey Bull. 582, p. 53, 1915.

¹³ Idem, p. 53.

¹⁴ Ransome, F. L., The geology and ore deposits of the Bisbee quadrangle, Ariz.: U. S. Geol. Survey Prof. Paper 21, pp. 51 et seq., 1904.

^{14a} Jenkins, O. P., and Wilson, E. D., op. cit., p. 11.

already mentioned. In these small outcrops no fossils were seen, but it seems not unlikely, because of lithologic similarity, that they are westward remnants of the Mesozoic formations.

IGNEOUS ROCKS.

The igneous rocks which are thought to be Mesozoic are difficult to distinguish from the pre-Cambrian rocks without detailed study. In general they are characterized by lack of sheeting and gneissoid structure, and by the fact that many of the granitic types have both orthoclase and plagioclase feldspars.

In the Santa Rita and Patagonia mountains the Mesozoic igneous rocks, consisting of granite, granite porphyry, quartz monzonite, quartz diorite, aplitic and lamprophyric dike rocks, syenite, and gabbro, are intruded into the Paleozoic sedimentary rocks but nowhere cut the Mesozoic sedimentary rocks. The period of igneous intrusion is therefore thought to be pre-Cretaceous, or at the latest very early Cretaceous.¹⁵

At Silver Bell the Mesozoic intrusive rocks consist of alaskite, alaskite porphyry, biotite granite, andesite, and quartz porphyry.¹⁶

In the Sierra Estrella Schrader found biotite granite, granitic aplite, and pegmatite, which intrude older gneisses and schists. In the Sacaton Mountains he found mica diorite similarly intruded. These rocks he considers Mesozoic.¹⁷

The copper ores of Ajo occur as disseminated deposits in monzonite, or as vein deposits in rhyolite lava and tuff into which the monzonite is intruded.¹⁸ These two types of rock make up the eastern portion of the main part of the Little Ajo Mountains and are older than the conglomerate of the Ajo Peaks and the lava flows of Black Mountain. Older gneiss and schist which resemble the pre-Cambrian complex form the western part of the mountains. The igneous rocks that contain the ores, both the monzonite and the rhyolite, into which the monzonite is intruded, seem, because of their lack of intense dynamic metamorphism and their relation to the older crystalline rocks, to belong to the Mesozoic period of igneous activity.

In a number of localities in the Papago country were observed granitic and granitoid rocks containing both plagioclase and orthoclase feldspars, which probably belong to the same period of igneous activity. These localities are the Palo Verde Mountains, the mountains in the pass north of Table Top Mountains, the Maricopa Mountains near Estrella, O'Neills Hills, the Tule Mountains, and the

¹⁵ Schrader, F. C., and Hill, J. M., op. cit., p. 57.

¹⁶ Stewart, C. A., op. cit., p. 246.

¹⁷ Schrader, F. C., unpublished report on the Gila River Indian Reservation, Ariz.

¹⁸ Joralemon, I. B., The Ajo copper-mining district, Ariz.: Am. Inst. Min. Eng. Bull. 92, pp. 2011-2028, 1914.

Tinajas Altas Mountains. Fractured and altered porphyritic felsite of pre-Tertiary age was seen in the Papago Saguaro National Monument north of Tempe and in Growler Pass

TERTIARY ROCKS.

SEDIMENTARY ROCKS.

The sandstone and conglomerate found at a number of localities in this region are thought to be of Tertiary age. The evidence for their age is not definite but consists in their stratigraphic position and their similarity to rocks in the lower Gila region that are associated with calcareous beds from which Tertiary fossils have been collected.¹⁹ The close association of the conglomerate with the great sequence of lavas is probably the best evidence of its Tertiary age.

The beds included in this group are probably not strictly synchronous. Wherever their lower members were observed they rest on the eroded surface of the older rocks and are made up of angular debris derived from those rocks. In general the Tertiary sedimentary rocks are composed of coarse, poorly sorted arkosic material, such as is deposited by ephemeral streams in the same region to-day.

They are thus typical fanglomerates as defined by Lawson.²⁰ In some localities so much tuffaceous material is included that it is evident that they were deposited during the volcanic period. Outcrops of the rocks were studied at nine localities, which are shown upon the geologic map (Pl. IX). The beds range in thickness from 50 feet to more than 1,000 feet and are, without exception, dislocated and extensively eroded.

VOLCANIC ROCKS.

Distributed throughout the Papago country is a great series of volcanic rocks which range in chemical composition from siliceous rhyolite to olivine basalt. In some localities, as in the Sand Tank and Saucedá mountains, they formed a great mantle of flows and tuffs which almost completely buried all the preexistent rocks. In the Growler, Ajo, Saucedá, Quijotoa, and Sand Tank mountains the thickness of lava is commonly 1,200 to 1,500 feet and may reach 2,000 feet. In other localities the lava is thin or lacking, and in the Tumacacori Mountains tuffs predominate over lava flows. All these lavas have been dislocated and dissected. The dissected slopes merge with the mountain pediment (see pp. 52-53) or are buried in alluvium, and this characteristic indicates that all the lavas are probably older than the Pleistocene. In contrast to them the Pleistocene basalt lies on top of the alluvium in the valleys and is but little dissected.

¹⁹ Ross, C. P., *op. cit.*, pp. 188-190.

²⁰ Lawson, A. C., The petrographic designation of alluvial-fan formations: *California Univ. Dept. Geology Bull.* 7, pp. 325-334, 1913.

Most of the centers of eruption from which the Tertiary volcanic material emerged are either concealed by later flows or removed by erosion. Much of the lava may have been extruded from fissures, and volcanoes may never have been prominent features of the Tertiary landscape. However, Batamote Mountain has the form of a slightly dissected volcano, and the mountain south of Kaka appears also to be an old volcano.

The variety of rocks included in this series is illustrated by the work of Guild in the Tucson Mountains.²¹ He found rhyolite, rhyolite tuff, biotite-hornblende andesite, pyroxene andesite, pyroxene-mica andesite, and several basalts.

In the Tumamoc Hills Tolman²² found the following succession, beginning with the youngest: (1) Basalt flows and intrusions, (2) rhyolite tuff, (3) two basalt flows, (4) andesite flows. These rocks he considered to be of Pleistocene age, but because they are uplifted, faulted, and dissected they are here mapped with the Tertiary.

In the Santan Mountains Schrader²³ found 100 feet of olivine basalt overlying 200 feet of latite, which in turn rests on granite of the crystalline complex. These rocks increase in thickness toward the center of the Malpais Hills, in which they occupy an area of about 9 square miles. Basalt also occurs at Walker Butte and in Poston Butte and other outliers of the Santan Mountains.

South of the Salt River Mountains lies Jackson Butte, separated from the mountains by a plain more than 2 miles wide, mantled by alluvium. The top of the butte is a bed of agglomeratic vesicular basalt about 20 feet thick. The lower part of the butte, which is masked by a talus of large blocks of basalt, is composed of unconsolidated gravel and sand. There is no near-by source of the basalt, and it is possible that the gravel conceals the plug that occupies the neck through which the basalt rose. The gravel also is much less consolidated than most of the Tertiary formations. The basalt of Jackson Butte may easily be of early Quaternary age.

The same remarks apply equally to a somewhat similar outlier on the east side of the Maricopa Mountains 1 mile north of Estrella station (Pl. XIII, B). This outlier consists of two small hills capped with 20 to 30 feet of dull-red felsite, which rests on arkosic gravel that separates it from the underlying crystalline rocks. The felsite forms beds 2 to 3 feet thick, of which the upper one is full of holes, like a vesicular basalt. The holes, however, are probably not due to the expansion of gases while the rock was hot but to the solution by

²¹ Guild, F. N., *Petrography of the Tucson Mountains, Pima County, Ariz.*: Am. Jour. Sci., 4th ser., vol. 20, pp. 313-318, 1906.

²² Tolman, C. F., *Geology of the vicinity of the Tumamoc Hills*: Carnegie Inst. Washington Pub. 113, pp. 67-82, 1909.

²³ Schrader, F. C., unpublished report on the Gila River Indian Reservation, Ariz.

weathering of some constituent of the rock. The gravel is similar to that of the present streams and is but a thin coating on an old surface of erosion that has been uplifted and now stands above the level of the adjacent pediment.

QUATERNARY DEPOSITS.

ALLUVIAL MATERIALS.

GENERAL CHARACTER.

The Pleistocene and Recent materials have been derived from the erosion of the present mountains and laid down by existing streams or their counterparts. The climate of Quaternary time has not been uniform, though doubtless it has been throughout of the arid type. Variations in climate may be assumed because of the known fluctuations throughout the world shown by the glaciation of large areas, and also because in Arizona there were permanent lakes where now there are only temporary lakes.²⁴ The fluctuations in this region were, however, not so great as to bring about a humid climate. The change was only in the degree of aridity.

Thus the deposits of the different stages of Quaternary time are similar to one another and vary chiefly according to their topographic position. Near the mountains ephemeral streams build up alluvial fans of coarse, poorly assorted gravel. Farther down the slopes the same streams deposit finer debris as sandy clay and fine gravel and sand. Near the middle of the valleys clay or sandy clay may predominate, though wind-blown sand and lenses of sand or gravel are also deposited, the material being dependent on the type of the axial stream. Thus if materials of one of the older Quaternary stages originally laid down near the mountains are exposed near recent deposits of streams at a distance from the mountains the contrast between the two deposits is great. But if deposits of the two stages were both laid down by essentially similar streams in corresponding portions of their courses they may be so similar that it is impossible to tell them apart. In general those beds of alluvial material which stand above the general level and are now being eroded are regarded as belonging to the earlier stages, and these beds are commonly cemented with caliche. Much larger amounts of the older deposits must be buried under the modern alluvial plains, however, and concerning these deposits little is known except such facts as are disclosed by well records.

The Quaternary deposits fall into three divisions—older alluvium, younger alluvium, and Recent deposits. These divisions can not be

²⁴ Meinzer, O. E., and Kelton, F. C., *Geology and water resources of Sulphur Spring Valley, Ariz.* : U. S. Geol. Survey Water-Supply Paper 320, p. 34, 1913.

definitely correlated with divisions of the Quaternary in other regions, however, nor can rigid application of these divisions be made within the Papago country.

OLDER ALLUVIUM.

The older alluvium is exposed at only a few widely separated localities, largely around the borders of the Papago country, though doubtless it lies buried beneath younger deposits in the greater part of the valley region.

Near Tucson red and partly cemented older alluvium is exposed near the base of the Santa Catalina Mountains at the mouth of Sabino Canyon. It is tilted and eroded, and on it rests the younger alluvium.²⁵ Field work by the writer in 1920 and 1921 indicates that this red material should be correlated with similar fanglomerates in the San Pedro Valley, which are of Pliocene age. Farther south, near Tubac, the bluffs along Santa Cruz Valley are doubly terraced, as shown in figure 23 and described on page 75. The gravelly deposits of the upper level seem to belong to the older alluvium; the lower terraces can be correlated with a part of the terrace and flanking stream-built slopes near Tucson. Similarly near Nogales the rock plains which border both Santa Cruz River and Nogales Wash, especially on their lower portions, are mantled with gravel. Near the streams these plains stand as bluffs about 150 feet high. The gravel that caps the bluff probably belongs to the older alluvium, whereas that on the rock bench about halfway down the bluff belongs to the younger alluvium.

On Gila River, east of the junction with the Salt, no outcrops of the older alluvium were found, but west of this point Ross²⁶ found only small areas of tilted gravel in the margins of the Gila Bend Mountains.

South of Wellton, lying against the northern border of the Wellton Hills, is a small tract of gravelly alluvium, which forms a plain about 50 feet above the alluvial slope. The slope is graded with respect to the base-level of the terrace about 100 feet above the flood plains at Wellton. The tract of alluvium is obviously older than the slope, and the slope seems to be of the same age as the terrace, which is regarded as part of the younger alluvium (p. 30).

North of Blaisdell and associated with an outcrop of red sandstone and clay of probable Tertiary age, is a deposit of gravel composed of rudely sorted materials with pebbles 1 to 2 inches in diameter in beds that dip about 10° W. The gravel has been bev-

²⁵ Smith, G. E. P., Ground-water supply and irrigation in the Billito Valley: Arizona Univ. Agr. Exper. Sta. Bull. 64, pp. 89-90, fig. 57, 1910.

²⁶ Ross, C. P., op. cit.

eled and more or less concealed by the outwash from the north end of the Gila Mountains. This outwash was deposited when Gila River stood at the level of the terrace of younger alluvium, and therefore the tilted alluvium must be older than the younger alluvium. It is, however, closely associated with the red sandstone and clay, and further work may show that both are Tertiary or perhaps that both belong to the older alluvium.

In the interior valleys of the Papago country the older alluvium can be identified positively only in Altar Valley. In these valleys the mountain pediments have a thin coating of alluvium, part of which is still being augmented by streams, but some of it lies above the present streams and is partly consolidated. Along the axial stream and the main tributary of Altar Valley, however, it seems possible to distinguish the older alluvium, as is more fully discussed on page 73.

YOUNGER ALLUVIUM.

Along Gila River there is a more or less continuous terrace from Gila Bend to Yuma. This terrace, cut into promontories by tributary streams, stands about 75 feet above the river. The surface is mantled with a coating of pebbles, in places only one pebble deep. Below the pebbles the terrace is composed of alternating beds of sand, clay, and gravel very similar to those laid down by the present river. The terrace, therefore, represents a period of aggrading of Gila River, at the conclusion of which the river stood at least 75 feet higher than it does now. All the tributaries were adjusted to this grade, and consequently the stream-built slopes of the adjacent mountains of the interior valleys slope to the top of the terrace. The cutting down of Gila River to or perhaps below its present level changed the base-level of the tributary streams, which with increased grade have cut valleys through the terrace. This headward cutting has been very effective on some of the tributaries north of Gila River,²⁷ but the tributaries on the south have been too feeble to dissect to any large extent the valleys which they drain. (See p. 68.)

Near Ligurta, 7 miles east of Dome, fossil bones were found on two promontories of the terrace that project into the flood plain of the river. The bones lay on the surface as part of the layer of pebbles resulting from the erosion of the materials which form the terrace. Near the river underlying beds are exposed in the bluff and consist of brown sand, gravel, and sandy clay similar to material now carried by Gila River. The clay has round, smooth concretions 3 to 12 inches in diameter. The brown sand has also many concretions, but they are rough on the surface and irregular in shape.

²⁷ Ross, C. P., *op. cit.*

A small sliver of bone was found in place in the brown sand, so that the bones are undoubtedly derived from it and probably are inclosed in the concretions. The bones were probably transported some distance before deposition, but it seems most reasonable to assume that the animals died on the river flood plain during the period of deposition of the brown sand.

A small collection of these bones was referred to J. W. Gidley, who identified the phalanx of a horse (*Equus* sp.) and the basal portion of the antler of a deer probably belonging to the genus *Odocoileus*. According to Dr. Gidley, "These fossils do not determine the age more closely than that they are Pleistocene, though the presence of horse remains suggests one of the older phases of the Pleistocene." The importance of even this indefinite dating is great, for it affords the first positive evidence of the Pleistocene age of the gravel of Gila Valley and establishes a datum point for the complex sequence of events worked out by Lee²⁸ and Ross.²⁹

In 1921 waterworn fragments of bone were found three-quarters of a mile east of Comobabi. (See map, Pl. IX.) At this locality the mountain pediment is developed on tilted fanglomerate similar to the Tertiary conglomerate of other localities. Resting unconformably on this conglomerate is a bed of gravel about 10 feet thick, which lies about 30 feet above present stream grades and perhaps belongs to the older alluvium. The gravel contains boulders of all sizes up to 3 feet in diameter and is similar to the channel gravels in the present streams. The upper 2 feet is thoroughly cemented with calcium carbonate (caliche). Below this part the cementation is less, and iron oxides are nearly as abundant as lime. The bones all occur in the lower 4 feet, and most of them were found in the lower 2 feet. The gravel was evidently deposited by the stream that eroded the pediment and presumably was deposited at or near the end of the period of erosion.

The fossils have been referred to J. W. Gidley, who reports as follows:

In the lot of fragmentary remains obtained 55 miles west of Tucson the only determinable material consists of portions of three teeth representing the genus *Equus*. One of these, a nearly complete upper molar of the right side. (catalogue No. 10443, U. S. Nat. Mus.), I refer provisionally to *Equus occidentalis*, a species described by Leidy in 1865,³⁰ from Tuolumne County, Calif. The specimens are too incomplete and the species too little known to make this determination positive, but in size and general characters the Arizona tooth agrees very closely with the type of the California species.

²⁸ Lee, W. T., Underground waters of Salt River Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 136, p. 112, 1905; Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, p. 67, 1908.

²⁹ Ross, C. P., op. cit.

³⁰ Leidy, Joseph, Acad. Nat. Sci. Philadelphia Proc., 1865, p. 94. Gidley, J. W., Am. Mus. Nat. Hist. Bull., vol. 14, pp. 14-16, fig. 10, 1901.

On the basis of this material no positive statement can be made regarding the possible age of the beds from which it came, for two reasons: First, although *Equus occidentalis* is usually considered a Pleistocene species, the fact, so far as Mr. Gidley is aware, has never been proved; second, there is no good reason why this particular species may not have found its way into the southwestern United States in Pliocene time and continued its existence there into the Pleistocene. It follows, therefore, that the paleontologic evidence regarding the age of the alluvium is at present of little value.

A small rodent jaw from Robles Well, on the Ajo road 25 miles west of Tucson, said to have come from a depth of 212 feet below the surface, Mr. Gidley has carefully studied and finds it can not be distinguished from similar jaws of *Neotoma albigulus*, a species of wood rat now living in that general region. He therefore concludes that it must have fallen into the well by accident from the surface.

The Gila Valley east of the Sierra Estrella is bounded by bluffs 25 to 50 feet high which, though not so high as those farther west, seem, like similar terraces on Salt River, to correspond to the 75-foot terrace of the lower part of the river.

Near Tucson a large part of the dissected stream-built slopes which terminate at the flood plain of Santa Cruz River belong to the younger alluvium. Farther south the lower terraces at Tubac and the gravel on the lower bench in the vicinity of Nogales may be correlated with it.

In the interior valleys the same difficulties of correlation exist for the younger alluvium as for the older alluvium. There are at a number of points, however, low terraces which probably belong with this formation. These terraces are described in the section on the valleys (p. 80), where such explanations as suggest themselves are offered.

RECENT DEPOSITS.

The Recent deposits comprise the sand and gravel in stream beds, the flood-plain deposits of the larger streams, and the deposits on the great flats of the interior valleys. These materials are all unconsolidated alluvium with minor amounts of wind-blown sand. They are more particularly described under the heading "Valleys," (p. 65).

BASALT.

Two flows of basalt covering extensive areas were poured out of low cones during Quaternary time. The great flow at Sentinel largely rests upon and protects the terrace of younger alluvium along Gila River and has been described by Ross.³¹ The other large area

³¹ Ross, C. P., op. cit.

lies in the southern part of the Tule Desert just west of Las Playas. It is a northern extension of the volcanic plateau surrounding the Sierra del Pinacate of Sonora and like that plateau appears to be of relatively recent geologic date. The volcanic character of the Sierra del Pinacate was first recognized by Father Eusebio Kino in his journey to the region in 1701.³² A biologic exploring party under the leadership of D. T. MacDougal mapped and described the region in November, 1907. Godfrey Sykes made a map of the region, showing the boundaries of the lava fields and the position of the principal craters.³³ Lumholtz, whose explorations in southwestern Arizona and Sonora resulted in an excellent map, found a legend among the Papagos referring to eruptions and ash showers from the two higher peaks.³⁴

The portion of the Pinacate lava flow which extends across the international boundary is a low mesa about 6 miles from north to south and 5 miles from east to west. The mesa rises from 50 to 100 feet above the Tule Desert, and this elevation seems to measure the thickness of the olivine basalt of which it is composed. The margins are but little dissected and seem to be near or at the original limits of the flow. Small cones and craters dot the surface. One of the cinder cones, a crescent-shaped ridge about 50 feet-high, is composed of very fresh-looking reddish slag, much of which was thrown out still molten and fell in pasty masses. Volcanic bombs are numerous. Though the bombs seem very fresh, the under side, where they lie on the surface of the ground, is covered by a film of calcium carbonate obviously derived from the weathering of the bomb. This coating or patina is thicker than that found on Papago artifacts in the neighborhood and may indicate that the Pinacate flows of basalt do not belong within the period during which the Papagos have lived in the region. Some weight, however, may be given to Papago tradition with respect to Recent eruptions in the Sierra del Pinacate.

STRUCTURE.

FAULTING.

The compressive movements of pre-Cambrian time can be recognized by the mashed condition of schists and phyllites, but the evidence of later folding has throughout the Papago country been

³² Bolton, H. E., *Kino's Historical memoir of the Pimería Alta*, vol. 1, p. 283, 1919. Kino also visited the Sierra del Pinacate in 1698 (*idem*, vol. 1, p. 187) and in 1706 (*idem*, vol. 2, pp. 205 et seq.).

³³ MacDougal, D. T., *Across Papaguería*: *Am. Geog. Soc. Bull.*, vol. 40, pp. 705-725, maps 1 and 2, 1908. Hornaday, W. T., *Campfires on desert and lava*, map opposite p. 110, New York, 1908.

³⁴ Lumholtz, Carl, *New trails in Mexico*, p. 203, New York, 1912.

stroyed by erosion. The scattered masses of Paleozoic rocks were disturbed, dislocated, and in part engulfed in Mesozoic intrusions, but post-Paleozoic folding has not been recognized. The Mesozoic sedimentary rocks are much disturbed in the Patagonia region,³⁵ where there is evidence of post-Cretaceous folding, but whether this movement extended westward into the Papago country is not known. Profound erosion had left a landscape of mountains of considerable elevation prior to the Tertiary lava flows, but the method of uplift of these mountains is not clear.

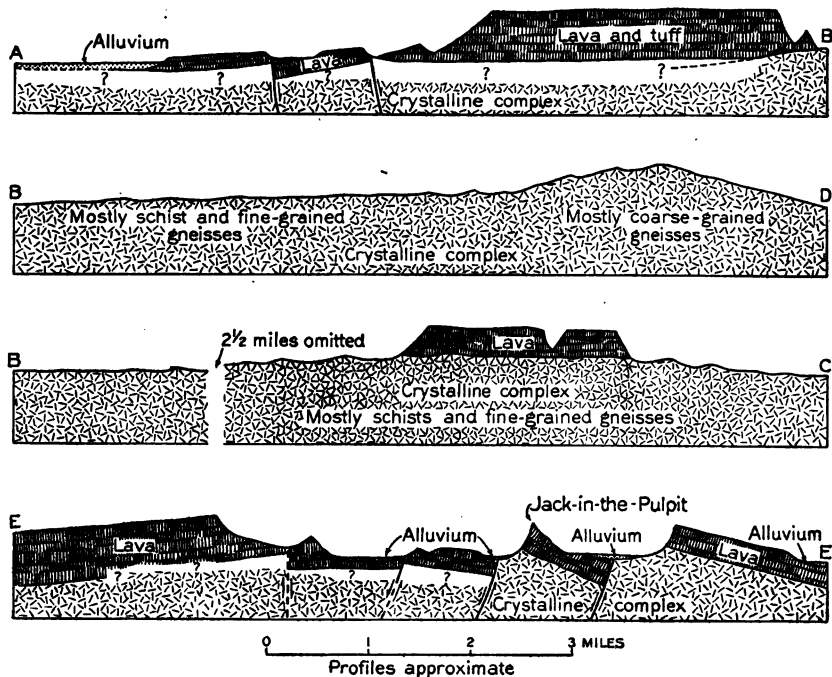


FIGURE 4.—Geologic cross sections in the western part of the Sand Tank Mountains, Ariz.

Faulting on a large scale, however, took place at the end of the Tertiary period of volcanism. To the movement which produced the faults of this period the present mountains owe their elevation, though there is evidence of Pleistocene movement along the same structural lines. The nature of the faults can best be illustrated by citing examples.

FAULTS IN THE SAND TANK MOUNTAINS.

The Tertiary lavas of the northwestern part of the Sand Tank Mountains are evenly bedded, and their whole thickness may be as much as 2,000 feet. The eroded surface of crystalline rocks appears

³⁵ Schrader, F. C., and Hill, J. M., op. cit., p. 77.

to have been fairly smooth, and consequently the lavas are immense plates of rock which, as at present broken by faults, resemble great flakes of ice stranded on a shore by the wind. Toward the east the lava flows are less continuous, the total thickness is more variable, and the individual fault blocks as revealed by the attitude of the lava plateaus stand out less clearly.

The faults are of the normal type and trend in two directions—north and east. The geologic map (Pl. IX) and the cross sections in

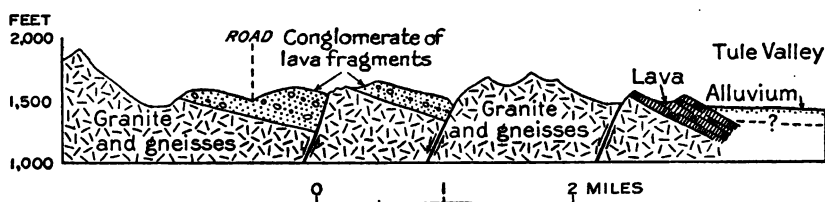


FIGURE 5.—Geologic cross section in the Tule Mountains, Ariz.

figure 4 show the effect of faulting on the distribution of the lavas and in the topography. Sections A-B, B-C, and B-D are arranged on a Y of which A-B is the stem. The faults shown in section A-B trend west of north and are marked by valleys. Along section B-D no lava appears, but a mountain of coarse-grained gneiss stands above the lavas which once covered it, at least in part. Along section B-C a lava plateau that has been uplifted, perhaps, but not tilted still resists erosion. Section E-E, at right angles to section A-B, shows the effect of the faults that have an easterly trend. Tilting of the

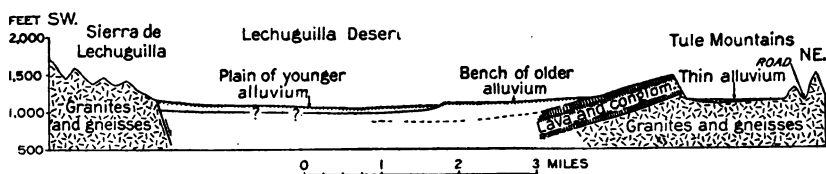


FIGURE 6.—Geologic cross section of the southern part of the Lechuguilla Desert, Ariz.

fault blocks is much more marked, and the underlying crystalline rocks are brought to the surface at the base of Jack-in-the-Pulpit and the plateau south of it.

FAULTS IN THE TULE MOUNTAINS.

In the pass southeast of Tule Well block faults are well shown by the tilted lavas and lava conglomerate which rest on a relatively smooth plain composed of the crystalline complex. The cross section in figure 5 brings out the character of these faults. On the west side of the same range and south of the road a great plate of lava and lava conglomerate about 750 feet thick dips westward under the Lechuguilla Desert (fig. 6). The contact with the crystalline

complex is exposed along the eastern face of the ridge. Hills several hundred feet high project up into the lava and indicate the local irregularity of the surface over which the lava flowed. North of the road what seems to be the same lava caps the mountains at an elevation about 1,000 feet higher. (See Pl. XI, *B*.) As shown in figure 6, the westward-dipping block of lava is bordered by a bench of alluvium about 50 feet above the level of the main Lechuguilla Desert. This bench of older alluvium indicates renewed uplift of the Tule Mountains in Pleistocene time, probably accompanied by faulting along the east front of the Lechuguilla Mountains. On physiographic evidence the Tinajas Altas Mountains, near by, are thought to have been reelevated in Pleistocene time.⁸⁰

FAULTS IN THE GROWLER MOUNTAINS.

The portion of the Growler Mountains north of Growler Pass is a rather simple monoclinical fault-block mountain trending northwestward and about 20 miles long. In the picturesque western escarpment are exposed between 1,200 and 1,500 feet of Tertiary lava, tuff, and conglomerate resting on the crystalline complex, which crops out in places at the foot of the mountain front. The eastern slope is gentle, almost without canyons, and conforms to the dip of the lava sheet.

In Growler Pass there are at least five faults that trend almost due north, but the intervening blocks are rotated in different directions. In the easternmost block the beds are horizontal. In the others the dips are easterly in two and westerly in two. The complex structure of Growler Pass continues in the southern part of the Growler Mountains, which consist of large lava plateaus, separated from one another by narrow canyons. The beds in each plateau dip at a different angle or in a different direction from those in neighboring plateaus, so that there must be a complicated system of faults.

GENERAL CHARACTER OF THE MOUNTAINS.

The mountains of the Papago country consist either of more or less isolated elevated regions separated by broad valleys underlain by alluvium, or of groups or chains of mountains separated by rather narrow alluvium-filled valleys or canyons. To the traveler crossing the country on the Southern Pacific Railroad the ranges appear to be rather monotonous in their characteristics, showing a recurrent sameness which implies a common geologic history. They seem to consist wholly of small detached sierras having very similar topographic forms, composed of granite and other coarse-grained crystalline rocks, and to be largely buried in alluvium. This appearance,

⁸⁰ Bryan, Kirk, Origin of rock tanks and charcos: *Am. Jour. Sci.*, 4th ser., vol. 50 p. 199, 1920.

however, is the result of the accidental distribution of certain types of ranges along the route of travel. A further exploration of the Papago country shows that many of the mountains are capped with lava beds much younger than the granite and crystalline rocks already mentioned and have the typical fault-block form common to the ranges of Nevada. Other ranges consist of exceedingly complex plateaus, peaks, and pinnacles, generally carved from thick lava beds. The ranges are thus by no means uniform in their rock composition and topography and they may be separated into groups according to their composition and structure. There are 70 mountain ranges and groups of hills in the Papago country,³⁷ and 11 more that lie east of Santa Cruz River are represented on the geologic map (Pl. IX). Of these 81 ranges 17 can not be described, because they have not yet been sufficiently explored. Of the remaining 64 ranges 2 are old volcanoes; 12 are rather simple fault-block or horst mountains, composed mostly of lava beds; 11 are similar faulted mountains of more complex structure; 21, composed mostly of pre-Tertiary rocks, have large or small areas of Tertiary rocks so disposed that they show that the mountains have been elevated since the Tertiary volcanic period, and many of them were already in the old-age stage of erosion when the Tertiary deposits were laid down and have been revealed by removal of the cap, as well as rejuvenated by uplift; 18 ranges are not known to have outcrops of Tertiary rocks, but at least two of them, the Tinajas Altas Mountains and Sierra Estrella, have been reuplifted in Pleistocene time.

PHYSIOGRAPHY.

INFLUENCE OF ARIDITY.

Erosion and sedimentation, the active geologic processes of the Papago country, are affected in their degree, methods, and results by the intense aridity of the region. Temperature and insolation vary but little, but with respect to average annual precipitation the Papago country may be divided into three parts. West of the Growler Mountains the annual precipitation ranges from $3\frac{1}{2}$ to 5 inches; between the Growler and Baboquivari mountains it ranges from 5 to 10 inches; east of the Baboquivari Mountains it is more than 10 inches, although not much more except in the Tumacacori Mountains. Though precipitation increases with altitude, the smaller mountains, averaging 2 to 4 miles in width and 1,000 to 1,500 feet in height, appear to have little effect on storms, and their vegetation does not indicate any large increase in effective rainfall over

³⁷ Bryan, Kirk, Geology and physiography of the Papago country, Ariz. (abstract): Washington Acad. Sci. Jour., vol. 10, pp. 52-58, 1920. Different figures are given because a smaller area was included in the "Papago country."

that of the adjacent plains. This is particularly true in the area west of the Growler Mountains. The mountainous district including the Sand Tank and Saucedo mountains probably receives a somewhat greater precipitation than the adjacent plains, as indicated by gramma grass and a slightly more luxuriant vegetation at the higher altitudes. In the same way greater precipitation on the Baboquivari Mountains is shown by scattered live oaks and other small trees not characteristic of the plain. Increase of rainfall due to increase of altitude is best shown in the Tumacacori Mountains, where there are orchard-like forests of live oak and a thick cover of perennial grasses. Even here the ease with which soil is formed on tuffaceous rocks and the consequent slow run-off may have as great an influence in producing the relatively heavy vegetative cover as increased precipitation.

MOUNTAIN SCULPTURE.

MOUNTAIN SLOPES.

The mountains of the Papago country rise from the surrounding plain with startling abruptness. To the traveler approaching them the mountain slopes stand like a wall, without transition from the plain on which he travels.³⁸ Only in a distant view is it possible to realize that the surrounding plain rises gradually on all sides toward the mountains, which stand up like jagged ornaments on the ridge-pole of a low-gabled roof.

This appearance is due to contrast in angle of slope between the mountains and the plain. The angles of the mountain slopes range from 15° to almost 90° with the horizontal; those of the plain from 1° to 6°. Between these slopes there is usually no region of transition, either of intermediate slopes or of low foothills. In many ranges slopes that average 25° to 30° rise directly from the plain to the crest of the mountains. The factors which produced the mountain slopes must then differ radically from those which produced the plain.

CONDITIONS DETERMINING MOUNTAIN SLOPES.

Mountains composed of rock of any one type have a relatively constant angle of slope, either at the mountain border or in the side walls of canyons. Even small isolated hills have similar slopes. These conditions have been stated by Lawson³⁹ as follows: "(1) That the hard-rock slopes of desert ranges which shed large spalls are steep, while those which shed small fragments have a low angle;

³⁸ Hornaday, W. T., *op. cit.*, pp. 38-39 (a humorous statement of these facts).

³⁹ Lawson, A. C., *The epigene profiles of the desert*: California Univ. Dept. Geology Bull., vol. 9, p. 29, 1915.

(2) that ranges composed of hard rock, which are thus naturally steep, maintain their steepness as long as the rock slopes endure."

The resistance of rock to weathering is the dominating condition which determines the angle of slope, but the presence of large spalls is only one of the results of resistance to weathering, though in many types of rocks there is a significant relation between the size of spalls and the angle of slope, as noted hereafter. Resistance of rock to weathering seems to be divided into two phases—resistance to the detachment of large blocks and resistance to direct weathering into small particles. Both kinds of resistance involve mechanical and chemical processes of weathering, but in the Papago country, because of the arid climate, mechanical processes are dominant.

MECHANICAL PROCESSES OF EROSION

The mountain slopes are ordinarily barren of soil, the bedrock presenting an uneven surface, the lowest parts of which are covered by a layer of broken rock fragments but recently parted from the parent rock. The projections of the bedrock are large or small, according to the spacing of joints. Weathering proceeds along the joint planes, and the projections tend to be detached and then lie on the surface as blocks or boulders or, as Lawson speaks of them, "rock spalls." In many places the surface is completely mantled by blocks and boulders. The production of blocks of this character is accomplished in part by the weakening of cement and widening of joints by solution but largely by expansion and contraction of the rock under the influence of changes in temperature.

Daily as well as seasonal changes are very large, the mean daily air temperature in January, the coldest month, being 54.7° and that in August, the warmest month, being 90.1° . At mid-day the temperature of the soil and rock is frequently higher than that of the air, whereas at night the rock cools nearly to air temperature.

The depth to which changes in temperature are effective in disrupting rock can only be estimated. The water of wells dug wholly in rock has the temperature of the surrounding rock, from whose crevices and seams it seeps. Water standing only 59.5 feet from the surface in Al John's well at Gibson, on the east flank of the Little Ajo Mountains, had a temperature of 67.5° on October 10, 1917, and doubtless represents the mean annual air temperature for that locality, as it is only 1.6° below the mean annual air temperature at Ajo for the years 1915 to 1918. In the vicinity of this well seasonal changes of temperature do not penetrate perceptibly below 60 feet. However, the well is in an interstream area of gently rolling country, and it is not unlikely that on the crests of the ridges insolation is effective to greater depths. In the valleys, where the water table is

nearer the surface, the reverse is probably true and insolation is effective to depths of about 25 feet, the depth at which water ordinarily stands in wells.

The daily changes in temperature produce effects much more striking and probably more effective in the breaking up of rock than seasonal changes. The effects may be summed up under three heads—rupture and spalling, exfoliation, and granular disintegration.

Rupture appears to be due to the expansion of rock under the influence of a rise in temperature beyond the elastic limit of the material, doubtless followed by sudden cooling as suggested by Walther.⁴⁰ It is most often observed in fine-grained brittle rock, such as siliceous lava. The action affects blocks of rock lying loose on the surface which are from 1 to 2 feet through in the direction of minimum thickness. The rupturing takes place on sharply defined but irregular planes and apparently in a single action, for the broken surfaces, though all manifestly younger than the exterior of the block, have a uniform color, corresponding to the time they have been exposed to the weather, but show no marks of weathering along initial cracks. Similar rocks suffer also from the spalling off of slivers, which in many places are scattered about like the quarry refuse left by Indians in making stone arrowheads. Though this process is most easily observed in loose blocks of rock, it undoubtedly affects the bedrock also, and thus in its ultimate effect it grades into exfoliation and serves to break up the plates formed by that process.

Exfoliation is a process by which successive surface sheets of rock are parted from the underlying mass. The surface of a rock mass, being in contact with the air, changes in temperature from hot to cold or from cold to hot more rapidly than the interior. As a consequence of the resultant changes in volume, the surface shell is either too large or too small for the interior. Shearing strains are set up between the shell and the interior and a crack forms. The thickness of the shell varies according to the area and form of the surface exposed to the air and the texture of the rock. When first exposed to this process rock masses are commonly angular and bounded by joint planes. The first places attacked are the corners and edges, where heat is most readily absorbed and radiated. The first parting plane is commonly 3 to 4 inches below a corner and thence approaches the surface in all directions, so that the first fragment to break off is a four-sided piece whose lower surface is concave. With the splitting off of successive sheets, each of which is slightly thicker at the protuberances of the rock, the remaining mass approaches a spherical shape. In the Papago country exfoliation sheets from one-fourth of an inch to 2 inches thick have

⁴⁰ Walther, Johannes, *Das Gesetz der Wüstenbildung*, p 29, Berlin, 1900.

been observed on granite, from an inch to 2 feet thick on arkosic conglomerate, and of almost paper thinness on certain felsitic lavas. To exfoliation may be attributed the rounded bosslike forms that occur on most outcrops of the Tertiary arkosic conglomerates. Figure 11 (p. 50) shows the relation of these curved surfaces to joints, and the hill on the right in Plate X, A, shows both the bosslike surfaces and the niches mentioned on page 50.

Exfoliation sheets from 6 inches to 2 feet or more in thickness are recognized only on rocks that have few joints and very massive structure. It seems likely that these sheets are produced by seasonal changes in temperature. In rocks with more closely spaced joints yielding takes place along existing fractures or by the reopening of older lines of weakness. Thus in such rocks the curved forms of exfoliation are not produced.

Granular disintegration is due to the unequal rates of expansion of different minerals whereby a rock composed of more than one mineral is subject to internal strains with every change in temperature. These strains tend to separate the different mineral grains one from another and thus to reduce the rock to a loose rubble. The process is best observed in coarse-grained granite and is probably the most effective type of weathering in this rock.

CHEMICAL PROCESSES OF EROSION.

The freshness of rock débris, the lack of soil, and the absence of chemical deposits all testify to the preponderance of mechanical over chemical action in the Papago country. Though chemical action is not large in amount, however, evidence of its presence is widespread, and its total effect is likely to be underestimated.

Chemical action is dependent on the presence of water and is most active in regions of circulating water, abundant organic matter, and high temperature. Few of the rocks of this region are ever saturated with water or are even wet frequently, yet water circulates in the joints and adheres to the walls of all cavities and pore spaces for a considerable time after each wetting. It is also possible that moist air in the cracks of the rocks may be effective in chemical work on the side walls. Prospect holes and other excavations show few joints which are not widened by solution or along which rock decay is not evident. Even loose boulders are marked by concentric bands of color showing solution and redeposition, particularly of the iron minerals. In the mines at Ajo copper sulphides are oxidized to depths of 20 to 150 feet.⁴¹

⁴¹ Joralemon, I. B., The Ajo copper-mining district, Ariz.: Am. Inst. Min. Eng. Bull. 92, pp. 2011-2028, 1914.

Rock *débris* seldom shows grains of hornblende or biotite mica, for these minerals are largely destroyed by chemical action before the rock breaks up. In certain localities in the Papago country granite surfaces are pitted by the removal of these minerals and subsequent mechanical disintegration is facilitated. The feldspars, on the other hand, are very fresh and clear and rarely have the dull-reddish opaque appearance which they assume in the residual soils of the Sierra Nevada and central New Mexico. Solution of the glassy matrix of lavas is also a fairly rapid process and probably plays a large part in the removal of lava blocks on talus slopes.

GRADES OF MOUNTAIN SLOPES.

Mountain slopes range in steepness from vertical cliffs to grades up which it is easy to ride a horse. Slopes can be divided into three groups—cliffy slopes, boulder-controlled slopes, and rain-washed slopes. The limiting angles and characteristic rocks of these groups are shown in figure 7. Each group has certain common characteristics,

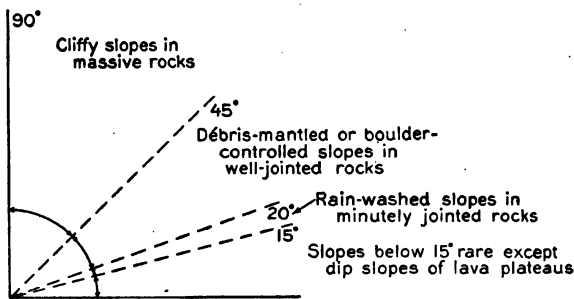


FIGURE 7.—Diagram to show the range of mountain slopes.

although the dividing lines between them are not very sharp.

CLIFFY SLOPES.

Mountain slopes inclined between 45° and 90° from the horizontal are developed on granite, granite gneiss, massive

lava beds, intrusive fine-grained porphyritic rocks, and arkosic conglomerate. These cliffy slopes are stable under the existing conditions of erosion, and the mountains composed of suitable rocks grow smaller in size but maintain the same angle of slope until they are totally reduced. The rocks are massive, with widely spaced joints, and the steepness of slopes seems to be related to the sparse jointing, for near by may be found the same rocks with more closely spaced joints undergoing erosion on gentler slopes. In sparsely jointed rocks joint blocks are not easily dislodged, and the mountain slope recedes either by undermining at the base or simply by surface disintegration and weathering of the rock wall. When at long intervals blocks are dislodged, they have been so weakened by weathering that in falling to the base they break into fine rubble. Thus no talus forms at the foot of these slopes. Slopes of this type on arkose are shown in Plate X, A, on massive lava flows in Plate X, B, and on granite in Plate XII, A.



A. AJO PEAKS, ARIZ., FROM THE EAST.

Cliffy slopes of Penasco Peak developed on massive Tertiary conglomerates and dissected pediment in foreground. Exfoliation and niches on bosslike hill at the right.



B. CLIFFY SLOPES OF MASSIVE LAVA FLOWS ON THE WEST SIDE OF THE AJO MOUNTAINS, ARIZ.

Montezuma head in the left center.



A. GROWLER MOUNTAINS SOUTH OF BATES WELL, ARIZ., FROM THE WEST.

Unbroken, talus-controlled slopes developed on slightly tilted lavas.



B. LAVA-CAPPED MOUNTAIN IN THE CABEZA PRIETA MOUNTAINS, ARIZ., FROM THE WEST.

Gullied lava talus and, to the right, mountain slope on granite with talus one boulder deep.

BOULDER-CONTROLLED SLOPES.

Mountain slopes inclined between 20° and 45° from the horizontal are characteristic of most granites, granite gneisses, and horizontally bedded lava flows. The angle of the common mountain slope is between 30° and 35° . The steeper slopes are usually interrupted by cliffs, and the gentler ones are interrupted by slopes of the next class.

Mountain slopes of this type composed of bedded lava flows consist of a cliff with talus below, successive cliffs with intervening talus, successive cliffs with smooth intervening slopes developed on tuff, continuous talus, or talus gullied and dissected. Very thick and massive lava flows resist the dislodgement of joint blocks and form cliffs. Whether these cliffs lie at the top or midway of the slope, they simply retard the recession of the mountain slope and increase its average steepness. The processes on the intervening talus slopes are similar to those described below.

Smooth slopes on tuff recede more rapidly than the cliffs above them, and the undermined blocks roll down over them. Only where such slopes are short stretches intervening between two steeper slopes are they free of rock waste. Where they are bare, the processes of erosion on the tuff are those described for rain-washed slopes (p. 46).

Bedded lavas under the attack of weather usually break into joint fragments from 2 to 6 feet in diameter, which, although easily dislodged, are comparatively resistant to disintegration and hence form a talus of rock waste that gradually mantles the whole mountain slope. The grade of the slope then becomes the angle of repose of the average-sized joint fragment (Pl. XI, A). Further erosion takes place by removal of the rock waste and formation of a new talus.

On certain mountain slopes part of the talus is removed by the formation of gullies, as shown in Plate XI, B. The mountain here illustrated consists of a cap of lava on a base of granite, and because of the difference in color the gullied talus is easy to photograph. Other mountains similar in size and composed wholly of lava have like gullies with like triangular areas of unremoved rock waste. Figure 8 shows the distribution of gullied and ungullied mountains of flat-lying lavas of approximately the same size and height observed in the Papago country. Many others of both kinds exist, and only those observed are included.

No local lowering of base-level is evident at the foot of these mountains, and the formation of the gullies can be ascribed only to the work of unusually heavy local rains. Such rains are well known under the term "cloud-bursts," and if disintegration of the boulders that form the talus and the bedrock on which they lie had proceeded until an unstable condition had been reached a single cloud-burst

would be competent to produce the gullies. Weathering and the normal rains combine to dislodge new fragments, which will in time fill the gullies and restore the original unbroken mantle of rock waste.

Confirmation of this explanation is obtained from the talus slopes of the ungullied mountains. The greater part of the rock waste has been in position for a long time. The boulders are cracked, exfoliated, and pitted by the solution and removal of the ferromagnesian minerals. The under surfaces of the boulders are coated with calcium carbonate derived from solution of the minerals. Bushes grow

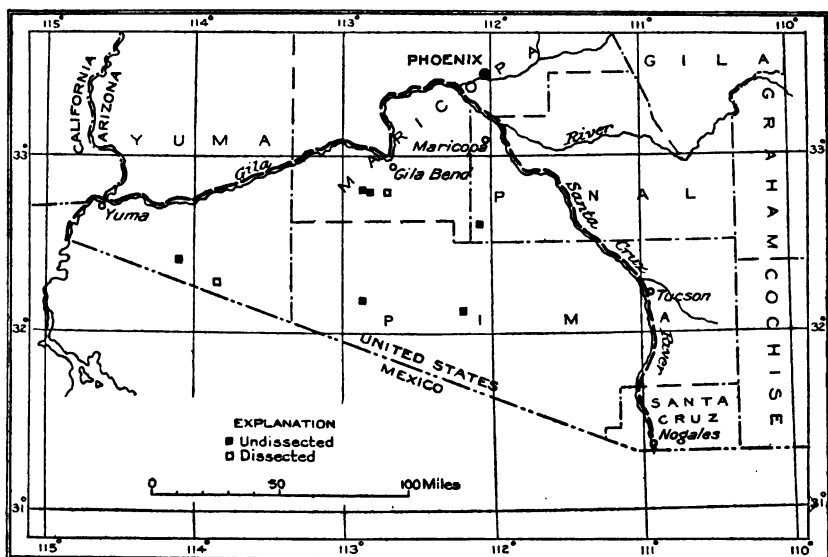


FIGURE 8.—Sketch map of the Papago country, Ariz., showing distribution, so far as observed, of gullied and ungullied mountains of approximately the same size.

between the boulders. Of these the most significant in indicating the stability of the slopes is the palo verde, *Parkinsonia microphylla*, whose age on the slopes of Tumamoc Hill was found to range from 10 to 400 years.⁴² In contrast to this ancient rock waste strings and lenses of fresh rock waste occur on all slopes. The blocks are sharp-angled and more closely packed than those of the older rock waste and occupy positions corresponding to the gullies previously described.

The retreat of a talus slope on horizontal lavas takes place by the slow production of the fragments that compose the talus blocks, by their decay, and by the creep of the rock waste from top to bottom of the slope. This slow process is occasionally interrupted by the

⁴² Shreve, F., Establishment and behavior of the palo verde: Plant World, vol. 14, p. 293, 1911.

catastrophic removal of large amounts of rock waste by great storms, exposing a fresh rock surface from which rock waste is again gradually produced and the talus is replaced.

Granite slopes at angles between 20° and 45° also have a mantle of rock waste, although it is by no means so nearly complete as the talus on lava slopes, particularly on the steeper slopes. The talus on granite slopes commonly consists of a layer of boulders only, and in many places scattered boulders and patches of boulders between protuberant knobs of the bedrock seem to determine the angle of the slope. The granite boulders range from 10 feet down to 1 foot in diameter, and all sizes may be found on a single slope, but in a general way the size of the boulders is proportional to the grade of the slope. Large boulders mantle steep slopes, and small boulders gentle slopes. As the size of the boulder is determined primarily by the spacing of joints, fine-grained granite and most granite gneisses, which usually have closely spaced joints, yield smaller boulders and consequently produce gentler mountain slopes than coarse-grained granite and gneiss.

Many of the granite boulders have a brown or blackish color from the so-called "desert varnish," which is associated, in granite at least, with the deposition of limonite in the outer 1 or 2 inches of the rock. This outer crust is in many boulders a shell which covers a completely disintegrated interior so soft and crumbling that the minerals may be picked apart with the fingers. Many boulders also are cracked, and some are completely split, many of them in two or three directions. Still others show the work of exfoliation. On many mountain slopes the boulders are so weather beaten and ancient in appearance that it seems that they could not possibly have been produced by any process now in action, but that, laid on the slope in some ancient time, they have ever since been slowly rotting and disintegrating.

The bedrock on which the boulders lie is covered with a loose film of small fragments made up of the mineral grains that once formed the granite. The fragments slip under the foot, and new pieces crumble from the bedrock continually. Disintegration of the bedrock proceeds most rapidly along joints but is effective everywhere. Every rainstorm sets trains of this fine *débris* moving down the slope. As the fine *débris* is removed the boulders roll down to find a new lodgment either lower on the slope or at its base. In this movement many of the boulders, already disintegrated within the outside crust, are shattered into fragments. Under normal conditions few of them reach the bottom and no accumulation of boulders takes place there.

As the bedrock disintegrates and rain washes the *débris* away more rapidly along joint planes protuberances of the bedrock are formed,

which consist of the most compact rock between the most widely spaced joints. The protuberances are cut loose by the same process that formed them, and a new crop of boulders comes into existence.

By these slow but continuous processes the mountain front recedes, but the same great storms that affect the slopes of lava mountains fall on granite slopes also. The process of recession is doubtless hastened by these storms, but no direct evidence of their effect has been obtained.

RAIN-WASHED SLOPES.

Mountain slopes at angles less than 20° from the horizontal are rare in the Papago country. They are developed on the least-resistant rocks, which, probably occurring in relatively small amount, have been largely removed by erosion. The mountains are composed almost wholly of the resistant rocks, which thus dominate the mountain slopes and keep them at a relatively high angle, the gentle slopes occurring on hills and as parts of mountains.

Closely jointed gneiss, schist, phyllite, and felsite form gentle slopes. The closely spaced cracks absorb and retain more rain than those developed in rock of other types. These rocks usually contain also a larger percentage of soluble material, either of ferromagnesian minerals in the gneiss and schist or of glass in the felsite, and consequently chemical action takes place more readily when they are exposed to the weather. The processes of mechanical action, because of the smaller size of the joint fragments and smaller grain of the component minerals, tend to produce finer rock *débris*. This finer *débris* is readily moved by rain wash on a flatter slope than that on which corresponding material derived from granitic rocks can be moved. The joint fragments, being smaller, are also more easily moved and instead of falling are undermined and carried away by rain wash.

Tuff and shale also develop gentle slopes. The products of the weathering of these rocks are fine and rather easily produced, so that the angle of the slope is determined largely by the grade on which rain wash can transport *débris*. Certain tuffs, however, are so compact that they weather slowly and hence form steep slopes, the angle being determined wholly by the rapidity with which particles may be detached from the matrix.

CANYON CUTTING.

In the previous sections the recession of slopes has been considered. If rocks were absolutely homogeneous so that no irregularities were formed on slopes in which rain water could be concentrated, then mountains would be eroded wholly by slope recession. But when water is concentrated and flows in a stream it erodes the rock by corrasion at a rate faster than that of slope recession, and to this fact

is due much of the diversity of mountain topography and all the larger features of mountain sculpture in the Papago country.

Corrasion is wear by water in a stream and the rock débris which it transports upon the stream bed, and it is assisted by corrosion or solution of the rock so far as this may be accomplished by the passing water. The stream therefore cuts downward in a narrow groove, and in homogeneous material the walls are essentially vertical. Slumping and the processes of slope formation previously described operate to widen the cut so that in time each stream flows in a rather broad valley. As there is a limiting grade below which a given quantity of water can not transport a given quantity of material, corrasion

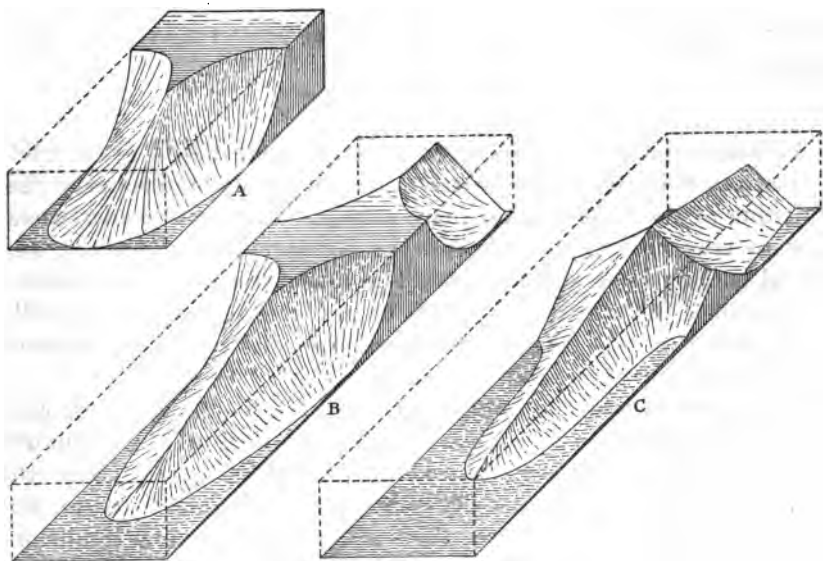


FIGURE 9.—Diagram showing three stages in the erosion of a block of the earth's crust to form the sierra type of mountain.

of the bed can proceed only until this grade is reached, and further lowering is prevented by the deposition of sediment. A stream which has reached this grade in any part is said to be graded.

The way in which canyon cutting produces the sierra type of mountain under the climatic conditions of the Papago country is shown in figure 9. In block A an original rectangular block of rock has been affected by erosion so that the face of the block has receded to the angle of 45° , assumed for the purpose of the diagram to be the slope normal to this type of rock. During the same time canyons whose side walls have the same slope of 45° have been cut into the block. In block B slope recession has carried back the point of the spur or ridge between the canyons, and the side walls of the canyon have also been eroded by the same process. Corrasion

has lengthened the canyon. At the mouth of the canyon and at the foot of the ridge a small pediment has been formed. By the recession of the canyon walls the crest of the ridge has been carried below the level of the original block. The ridge, then, has a slope which is a function of the original length of the block, the length of the canyons, and the angle of the mountain slope. In block C the canyons from opposite sides of the block have met, and the head of the canyon now assumes the grade of the mountain slope. From this time on stream erosion is at a minimum and the mountains decrease in size by slope recession and the lateral cutting of the streams on the canyon floors. It is obvious that if blocks similar to block C are placed on either side of it and others beside them, the typical sierra with its crenulated ridge and projecting spurs will be reproduced.

HEADWATER BASINS.

Although the erosive power of mountain streams is great when they are in flood, floods are so infrequent in the Papago country that widening of the valleys takes place slowly. The steep grades necessary to transport débris prevent the formation of meanders, and lateral cutting is at a minimum. The lower section of a mountain canyon, once the stream is brought to grade, is in consequence relatively stable in cross section, and the side walls recede by the slow processes of slope recession.

At the entrance of a tributary, however, there are two spurs, each bounded by one slope of the main canyon and one of the tributary. Here the recession of mountain slopes is doubly active. Near the divide several tributaries usually unite to form the main stream, and the corrugated surface between them affords the optimum conditions for slope recession. Hence, at such junctions headwater basins are formed.

If two or more streams develop such basins on either side of the divide, the divide may be reduced long before the rock mass lying between the lower portions of the streams is reduced. The production of headwater basins is accelerated, especially at the beginning of the process, by the more abundant rainfall which is characteristic of the higher parts of a range.

Development of these headwater basins is a common phenomenon in the Papago country, and part of one is shown in Plate XIII, A. Many mountains consist of groups of isolated hills, more or less irregular in size and height, scattered on plains, that rise to low divides which lie in the position of the original mountain crests and constitute merged headwater basins, or mountain pediments. Illustrations of these features are given under the heading "Mountain pediments" (p. 52).

MINOR EROSIONAL FEATURES.

The minor phenomena of erosion throw light on the processes that produce the larger features and the more common land forms. Of these phenomena the small caves or niches characteristic of certain mountain slopes are especially interesting.

Niches in coarse granite are common in the Tule and Tinajas Altas mountains. As shown in Plate XII, A, the niches are distributed from top to bottom of the mountain slope and range in size from holes 6 inches in diameter and 2 inches deep to caves 6 to 8 feet across at the mouth and 2 to 4 feet deep. In the cove at Tinajas Altas the niches may be conveniently studied. The granite, which on fresh fracture is white with a pinkish cast, has a mottled brown surface, in places rounded and bosslike between the joints. The brown color is due to the deposition of limonite in a crust usually about 2 inches thick. The niches are without this crust and thus evidently have been formed at a later date. The typical form is shown in figure 10. The roof and back walls have a rough surface, from which scales and fragments

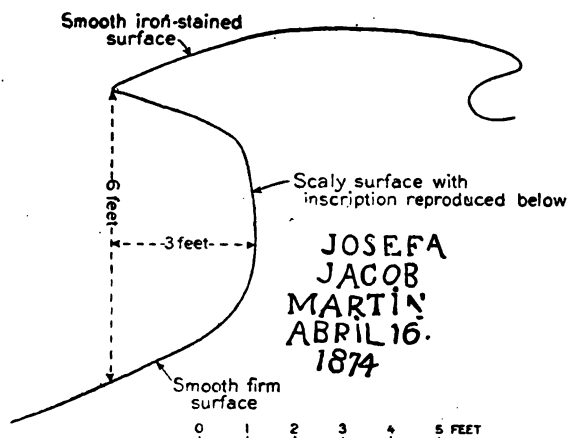


FIGURE 10.—Cross section of niche in granite at Tinajas Altas, Ariz.

of rock can be easily detached. The floor is usually firm and smooth and always slopes abruptly and continuously from the rear of the niche to the outside. On it are loose scales that have dropped from the roof and back walls.

The niches appear to be the work of insolation and solution, which, beginning at a place in the surface but poorly protected by the iron-stained crust, work inward, loosening successive flakes and chips. These fall and slip down the smooth floor, doubtless moving more easily when rain beats into the opening. Wind also may assist in removing the debris, but as the chips are ordinarily from a quarter to half an inch in diameter and an eighth of an inch thick, the wind is probably not an effective agent. The retreat of the back wall is not rapid. Some idea of the rate may be gained from the niche illustrated in figure 10. The inscription, "Josefa Jacob[a] Martin Abril 16, 1874," is evidently that of a traveler with the date of her

visit. It is painted on the rock with a paint made from the juices of a local bush and iron rust by a process well known to the Mexicans and Indians of the country. When visited October 21, 1917—43 years after it had been written—the inscription was in almost perfect condition except for the last “a” in “Jacoba,” which was lost by chipping of the back wall.

Niches very similar in appearance occur on the surfaces of the fantastic rocky hills carved from Tertiary arkosic conglomerate (Pl. X, A). These niches were studied in the Papago Saguaro National Monument, 7 miles east of Phoenix, where they are associated with rock shelters. The rock shelters are from 3 to 25 feet across and have an overhang of 3 to 10 feet; the niches are from 3 inches

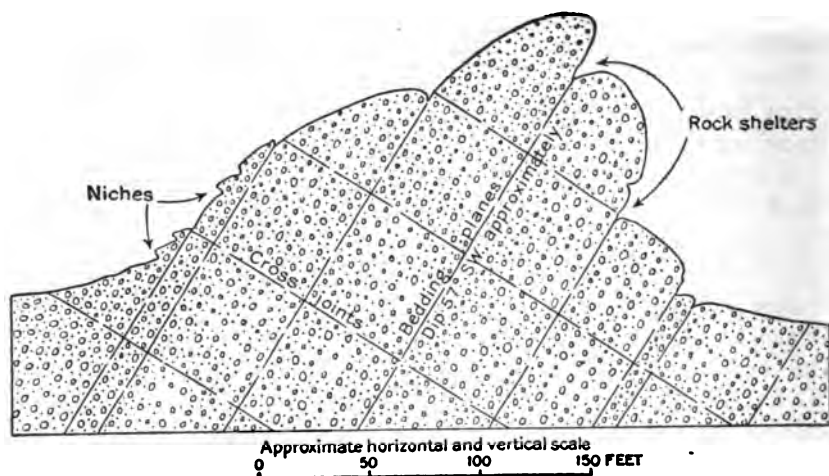


FIGURE 11.—Diagram illustrating weathering of Tertiary arkose conglomerate in the Papago Saguaro National Monument, Ariz.

to 3 feet in diameter and from a few inches to 3 feet deep, the depths being more or less proportional to the size of the opening.

As shown in figure 11, the shelters are due to erosion along the inclined bedding planes and joints. With the removal of certain joint blocks by exfoliation and disintegration, others are left standing with an overhang. Once the overhang is formed, erosion of the back wall begins through solution of the cement and even of the constituent boulders by rain water, which is absorbed by the overlying bare rock and thence seeps down and emerges in the shelter. Thus these rock shelters are formed in the same way as those in northern Arizona described by Gregory.⁴³

⁴³ Gregory, H. E., *Geology of the Navajo country*: U. S. Geol. Survey Prof. Paper 93, pp. 133–134, 1917.

The niches occur at intervals in the rock surfaces, and some are so small that they appear to be due to the dislodgment of single boulders from the matrix, and others appear to be due to solution along joint planes. Those of the predominant type are excavated in the rounded rock surfaces and may have no connection with joints. Their form is shown in figure 12. The roof of many of them is covered with red clay or a film of lime carbonate. The lower half inch to 1 inch of rock is separated from the main mass by a crack, and this flake can easily be detached. The back wall is usually rough, boulders of the conglomerate projecting into the niche. The floor slopes outward rather steeply and in many niches is covered with dust and fragments of rock. Joints of the cholla cactus (*Opuntia* sp.) are usually scattered about the floor, for the niches are favorite haunts of the trade rat.

The process of formation is clear. Beginning with a small cavity where a boulder has pulled loose from the matrix or where the cement has been dissolved at some particularly porous place, the niche is enlarged inward by the crumbling of the back wall and by the scaling of the roof, both due largely to seepage of rain water through the rock and consequent solution of the rock cement. The debris falls to the floor, along which it slides to the exit, transported principally by rain wash and water that trickles from the back wall.

Isolated pillars and monuments to which the Mexican gives the general name *peñascos* are commonly formed by the dissection of lava flows; less commonly they are formed of granite. In lava the formation of pillars is controlled by vertical joints in thick nearly horizontal beds. Pillars capping small buttes and mesas or isolated by erosion from a cliff are the common forms and add much to the picturesqueness of the plateau type of mountains. One of the best known of these pillars is Montezuma Head, in the Ajo Mountains, which on distant view resembles a square-shouldered gin bottle (Pl. X, B).

Pillars of granite usually consist of some massive portion of the rock from which the surrounding more closely jointed rock has been removed. Once isolated and attacked mainly by changes in tem-

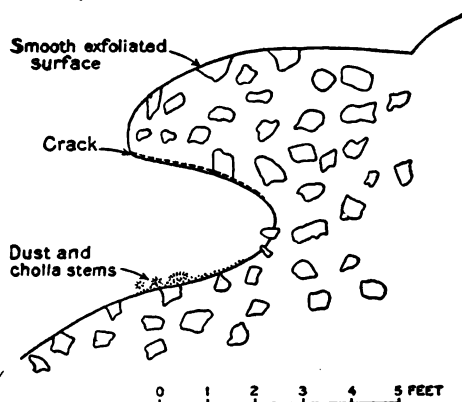


FIGURE 12.—Cross section of a niche in coarse conglomerate, Papago Saguaro National Monument, Ariz.

perature, a pillar resists the weather for a long time. Such a pillar on the crest of the Maricopa Mountains can be seen from the base of the Sierra Estrella across the whole width of the Jornada de las Estrellas.

MOUNTAIN PEDIMENTS.

CHARACTER.

In general, the mountains of the Papago country rise from plains which are similar in form to the alluvial plains that commonly front mountains of an arid region, but large parts of the plains

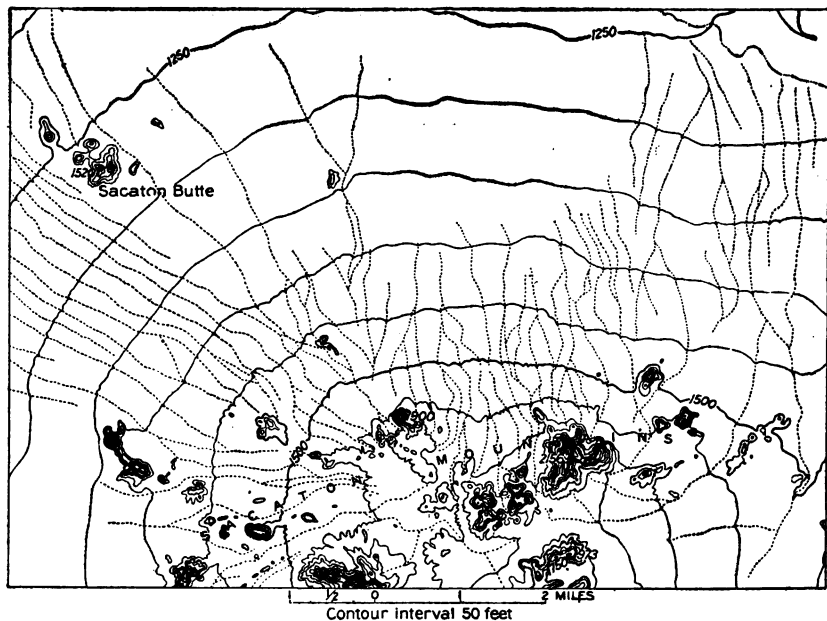


FIGURE 13.—Map of part of the Sacaton Mountains, Ariz.

are without alluvial cover and are composed of solid rock. These plains are called "mountain pediments," a term suggested by McGee's usage,⁴⁴ although he applied it to only one of the many similar plains cut on rock in the Papago country that he described. It corresponds to the terms "subaerial platforms" and "suballuvial benches" used by Lawson,⁴⁵ but certain differences in concept, as well as the awkwardness of his terms, make it advisable to substitute a term which does not imply any particular origin of the topographic form. The normal mountain pediment has smooth slopes, broken only by scattered hills that rise abruptly from the

⁴⁴ McGee, W J, Sheet-flood erosion: Geol. Soc. America Bull., vol. 8, pp. 92, 110, 1897.

⁴⁵ Lawson, A. C., The epiene profiles of the desert: California Univ. Dept. Geology Bull., vol. 9, p. 34, 1915.

plain and are more or less strung out in lines which are prolongations of the intercanion ridges of the mountains. Unfortunately no maps that cover large areas of normal pediment are available. The northern slope of the western part of the Sacaton Mountains is shown in figure 13. The plains around the hills and small mountains are cut on rock, but the northern part of the area shown has a heavy burden of alluvium. Schrader⁴⁶ states that the "subaerial or nearly subaerial eroded bedrock floor * * * seems to continue to within 3 miles of Casa Blanca," or to the vicinity of Sacaton

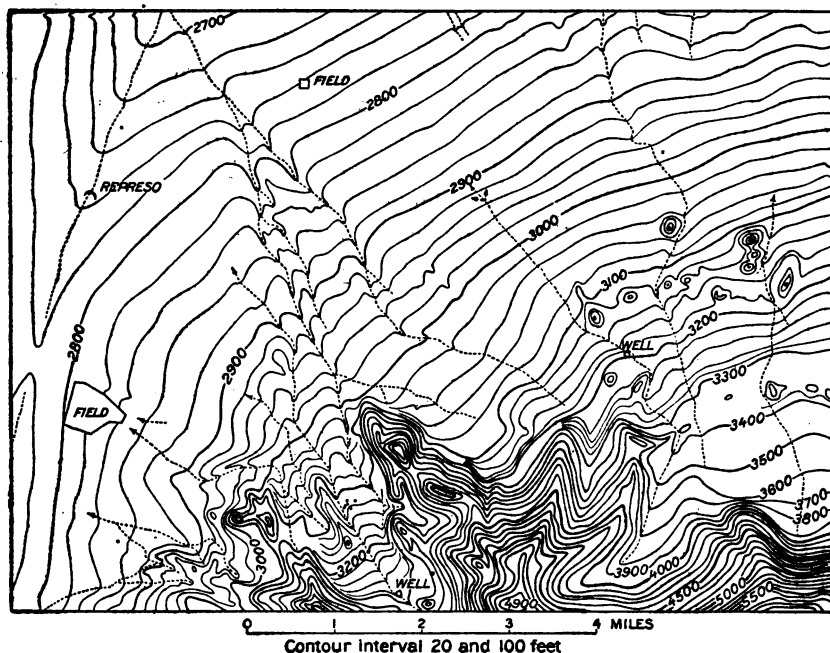


FIGURE 14.—Map of the northern border of the Baboquivari Mountains, Ariz. Redrawn from map by the United States Indian Service.

Butte. (See fig. 13.) Similarly figure 14 shows a pediment dissected by small canyons. This dissection is not so great, however, as to obscure the general form of the pediment.

The angle of slope of pediments ranges from about 50 feet to 200 feet to the mile. It is noticeable, however, that in any one mountain range the slope is steeper opposite the smaller canyons and very much flatter opposite the large canyons. The parts opposite the intercanion portions of the mountain front are steeper than the parts opposite canyons, and they commonly slope not only outward from the mountains but toward the stream channels, which emerge from the canyon mouths.

⁴⁶ Schrader, F. C., unpublished manuscript.

Exceptions to this general condition occur, for at the mouths of certain canyons the pediments have steep slopes, especially in the direction of the axes of the streams. This exception seems to be due to especially resistant boulders which have been brought down by the stream and dropped at the canyon mouth, causing the stream to spread and lose its carrying power. The boulders, until they weather into fragments small enough to be moved, protect and preserve a slope steeper than is normal to the pediment.

ORIGIN.

The mountain pediment is a plain developed at the foot of the mountains under the processes of erosion normal to the desert. The causes that produce the pediment are obviously different from those which produce the mountain slope. The key to these causes is found in the character of the loose material which covers the respective slopes. The mountain slopes are covered with loose boulders ranging in diameter from 6 inches to 5 or 6 feet. The pediment, on the other hand, is covered with fine fragments one-sixteenth of an inch to 6 inches in diameter.

Davis⁴⁷ recognizes that in the closing stages of an erosion cycle in desert regions graded rock floors will intervene between the alluvial slopes and the mountain slopes of an intermontane basin, just as he had previously recognized and shown these plains in a diagram in his discussion of the basin ranges.⁴⁸ Under conditions of extreme aridity the development of plains cut on rock does not necessarily indicate old age, but such plains may be produced earlier in the cycle and are dependent for their position on the upper limit of alluvial deposition in the intermontane valleys. Rock plains or pediments develop at or above the edges of the valley fill and are limited in size only by the available area and the factor of time.

As explained on page 42, the angle of slope of the mountain is controlled by the resistance of the rock to the dislodgment of joint blocks and the rate at which these blocks disintegrate. The angle of slope of the pediment, however, is due to corrasion by the streams, and this corrasion is controlled by the ability of water to transport débris, for the pediment is a slope of transportation intervening between the mountain slopes and the alluvial plain in the middle of the valley. Fine rock débris is moved down the mountain slope by rain wash and carried away from the foot of the slope by rivulets and streams that form through the concentration of the rain wash. The supply of this

⁴⁷ Davis, W. M., The geographical cycle in an arid climate: Jour. Geology, vol. 13, pp. 381-407, 1905; reprinted in Geographical essays, pp. 296-322, Ginn & Co., 1909.

⁴⁸ Davis, W. M., Mountain ranges of the Great Basin: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, pp. 129-177, 1903; reprinted in Geographical essays, pp. 725-772, Ginn & Co., 1909.

fine material on the mountain slope is, however, so small that it is readily removed, and the angle of the slope is determined by the size of the boulders. In the same way the fine material temporarily accumulating at the foot of the mountain slope by the breaking up of boulders, which have rolled down the slope, is usually carried away by the streams of the pediment as rapidly as it is supplied. The sharpness of angle between the mountain slope and the pediment is one of the most remarkable results of this division of labor between rain wash on the mountain slopes and streams on the pediment. The result, however, merely confirms the dictum of Noë and De Margerie⁴⁹: "The slope of an element of the surface is the more gentle as the force of the current active on that element is the greater."

In many localities the transition between mountain slope and pediment takes place in a belt which ranges in width from 100 to 200 feet. This change in gradient seems to be due to the abrupt concentration of rain wash from the mountain slope into streams on the pediment, though doubtless near the mouths of canyons lateral planation by streams is also an effective process, as suggested in a later paragraph.

In Lawson's excellent description of the forms developed by desert erosion he assumes that the débris from erosion of the mountains is poured into an inclosed basin, and consequently that the middle of the valley constantly rises through filling.⁵⁰ He states in substance that the alluvial slopes rise step by step with deposition in the middle of the basin, and their upper edges advance toward and finally engulf the mountains. On the same assumption Paige⁵¹ first stated the results in the following words:

The rising edge of the gravel sheet acts as an effective control below which erosion can not take place. The result is unavoidable if the time factor and the factor of area are sufficiently large. A process tending toward leveling with respect to the gravel sheet will proceed. But the gravel sheet has been gradually rising; therefore the leveled surface is a sloping plain thinly veneered with gravel.

In other words, erosion can take place only above the level of the alluvium and has its maximum value at the upper edge of the alluvial slope. On this hypothesis a plain is cut in the rock whose position and form are governed by the successive positions of the upper edge of the alluvial slope. With equal or diminishing increases in elevation of the middle of the valley in equal times the plain would have a curvature convex upward. With accelerated increase in elevation of the middle of the valley, which, however, must be slow enough to permit erosion of a plain and not so rapid

⁴⁹ Noë, G. de la, and Margerie, E. de, *Les formes du terrain*, p. 22, Service Géog. Armée, Paris, 1887.

⁵⁰ Lawson, A. C., *op. cit.*, pp. 30-31.

⁵¹ Paige, Sidney, *Rock-cut surfaces in the desert ranges*: Jour. Geology, vol. 20, p. 449, 1912.

as to bury the original surface, a plain of concave curvature would result. The convex type of plain which Lawson called a suballuvial bench is shown graphically in figure 15.

When, however, streams are able to maintain through drainage and there are no inclosed basins, the level of the middle of a desert valley may remain essentially stationary. A slope is established on the alluvial plain sufficiently steep for the transportation of the available *débris* by the available water. The edge of the alluvium then becomes relatively stationary, and as the mountain slope recedes a slope cut on rock is formed, which also is a slope of transportation. As the *débris* decreases in size with movement away from the mountain it can be moved on flatter slopes, and hence a pediment is concave upward.

The formation of pediments in the Papago country has been very generally interrupted by a new cycle of erosion, and the processes may now be observed only in localities of small extent. These

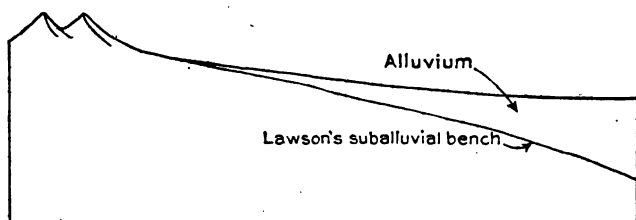


FIGURE 15.—Diagram showing the structural relations resulting from the slow but continuous filling of a structural basin.

processes will be briefly stated. At the base of a mountain front *débris* is swept outward by ephemeral streams which head in the mountain canyons and by small rills which originate through the concentration of rain wash at the base of the mountain slope. These streams are not permanent or even intermittent; they operate only during or immediately after rain.

From the larger canyons streams move pebbles as much as 6 inches in diameter, but this is the approximate limit in size, except on the east side of the Baboquivari Mountains and around the Tumacacori Mountains. These mountains are the highest and largest in the area and consequently have more rainfall and larger streams, in which boulders from 2 to 3 feet in diameter are not uncommon. In the stream channels a very rigid selection of material takes place; the finer particles move with every flood; the coarser material can be moved only by the larger floods. As the stream emerges from the mountains and its water spreads, the larger particles tend to be dropped and only the smaller ones are carried forward. Because there is an interval of time between floods, often a long interval,

the larger pieces are reduced in size by weathering and may then be moved by smaller floods.

At the base of a mountain slope the fine *débris* washed down by rains is moved forward by little rills toward the larger streams. As the supply of *débris* is small these rills are not fully loaded and are effective erosive agents, tending to reduce the height of interstream areas, but the grades on which they can work are steeper than those of the larger streams. Thus the pediment has a steeper gradient near the mountains between the canyon mouths and these portions also slope to the streams on either side.

The pediment is greatly increased in size by lateral migration of the streams at and below the mouths of the canyons. The irregularities of the pediment are removed, the higher places being eroded and the lower filled with *débris* and protected. The lower parts of the canyons are also widened by undermining the slopes of the intervening spurs.⁵² When the spurs become narrow they are cut through by slope recession on both sides, and hills are left standing as outliers on the pediment. These solitary hills are worn away with extreme slowness. Their erosion depends entirely on the gradual disaggregation of the rock which composes them and on the movement of the *débris* over the pediment during rains. The hills retain the same steep slopes as the original mountain but grow gradually smaller until the last remnants are masses of boulders or single rocks projecting above the general level.

The development of the pediment is therefore due to erosion, which may be summed up under three heads—(1) lateral planation by the streams issuing from the canyons, (2) rill cutting at the foot of mountain slopes, (3) weathering of outliers and unreduced remnants, with transportation of the *débris* by rills. The processes can not operate below a level determined by the grade necessary to transport *débris* away from the mountains. All depressions below this level will be filled up just as those above it are eroded. Thus the pediment is a slope of transportation and is usually covered with a veneer, from 18 inches to 5 feet thick, of *débris* in transit.

As transportation of relatively fine material by water is the essential factor in the formation of the pediment, in contradistinction to the erosion of mountain slopes, which is largely controlled by the movement of large boulders, it is obvious that the pediment grows most rapidly along the major streams. In every indentation in the mountain front and in places where streams emerge from the canyons onto the plains the rate of formation of the pediment is rapid, and consequently extensions of the pediment into the mountains are com-

⁵² Paige, Sidney, Rock-cut surfaces of the desert ranges: Jour. Geology, vol. 20, p. 450, 1912.

mon. These extensions consist of branching valleys, many of which are 2 miles or more in width and reach far into the interior of the mountain mass. The erosion of the mountains at the headwaters of many streams is much faster than in the lower portions of the same streams, for there is obviously more water pouring down the mountain slopes of the larger mountain masses, and feeble streams are incapable of much planation. Consequently the headwater slopes may recede more rapidly than the side walls of valleys. The extension of the pediment may thus divide the original mountain into groups of detached hills separated by relatively broad surfaces cut on rock, as in the Sacaton Mountains (fig. 13).

CONCEALED PEDIMENTS.

If the débris eroded from a desert mountain range and poured into the adjacent valleys is carried away by some through-flowing

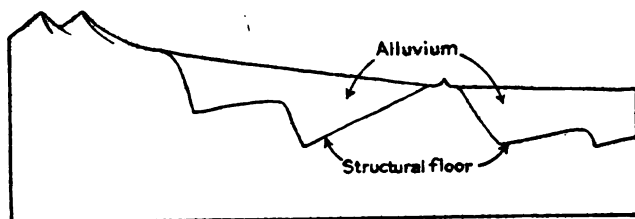


FIGURE 16.—Diagram showing the structural relations resulting from rapid and continuous filling of a structural basin.

stream and the base-level of erosion remains constant for an indefinitely long period, the pediment becomes simply the floor over which transportation is carried on, and as it is in a balanced condition between degradation and aggradation it can not be further lowered. On the other hand, if the adjacent valleys have no outlets or insufficient outlets sediment accumulates in them and the local base-level of the streams flowing from the mountains is raised. Deposition begins in the lower part of the stream courses, and the sediment gradually increases in thickness and extends toward the mountains. The edge and finally a large part of the mountain pediment may thus become concealed beneath a covering of alluvium.⁵³ A mountain pediment buried in alluvium may be called a concealed pediment.

If alluviation in the valleys proceeds slowly the formation of pediments will continue at and above the upper edge of the alluvium, but as this edge advances it will bury a surface convex upward, as postulated by Lawson. (See fig. 15.) On the other hand, accumulation of alluvium may be so rapid that the formation of a mountain pediment is not possible until a condition of stability is reached, and

⁵³ Paige, Sidney, op. cit., p. 449.

hence the alluvium covers and conceals a floor largely of structural origin, as shown in figure 16. A pediment may then form above the level of the alluvium, as illustrated in the figure.

A more complicated sequence of events is possible by which there is a slow but continuous filling of a structural basin with the formation of a suballuvial bench, a pause in alluviation during which an extensive pediment is formed, and then rapid filling that buries and conceals the pediment. This sequence is shown in figure 17 and is illustrated in part by an example described in one of the following paragraphs.

Identification of a concealed pediment is difficult, for the surface has the form of a normal alluvial slope and there is no surface indication of the buried rock floor. Large outliers such as characterize a pediment may not be wholly buried, but they can not easily be distinguished from projections above the general level of a structural floor. Positive identification of a concealed pediment must

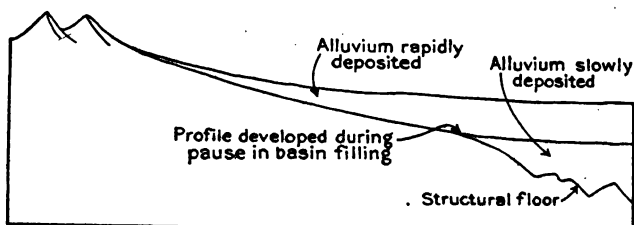


FIGURE 17.—Diagram showing the structural relations resulting from the discontinuous filling of a structural basin.

rest on excavations and wells which show alluvium resting on rock and also the form and character of this rock floor. The thickness of the alluvium must be greater than the ordinary depth of scour by streams, for pediments while being formed may have a shifting mantle of alluvium from 18 inches to 5 feet thick.

The presence of a concealed pediment may be inferred on a general physiographic argument, as illustrated by the following example. Westward-flowing streams in the Sand Tank Mountains, after passing across a large mountain pediment in which they are entrenched in little canyons below the general surface, flow out on grade into the Gila Bend plains (fig. 18). This alluvial slope is dominated by debris moving from the Saucedo Mountains northward to Gila River. The lava plateaus of the Sand Tank Mountains, which rise above the pediment on the east, are bounded on the west by talus slopes from 150 to 500 feet in height, whose lower portions are buried in alluvium. These slopes are the result of a considerable recession of the plateaus, for a continuance of the dip of the lava beds indicates that they once extended farther west, as shown in the cross section, figure 4 (p. 34). The large pediment east of the plateaus (Pl. XIII, A)

required for its erosion a period of time more than sufficient to provide for recession of these slopes and the formation of a corresponding pediment on the west side of the plateaus. Since then the pediment within the mountains has been dissected, but the same streams choked by a flood of alluvium derived from the Saucedo Mountains have buried the pediment on the western border.

COALESCING PEDIMENTS.

When a mountain range has been subjected to erosion for a long period of time, mountain pediments formed along individual streams

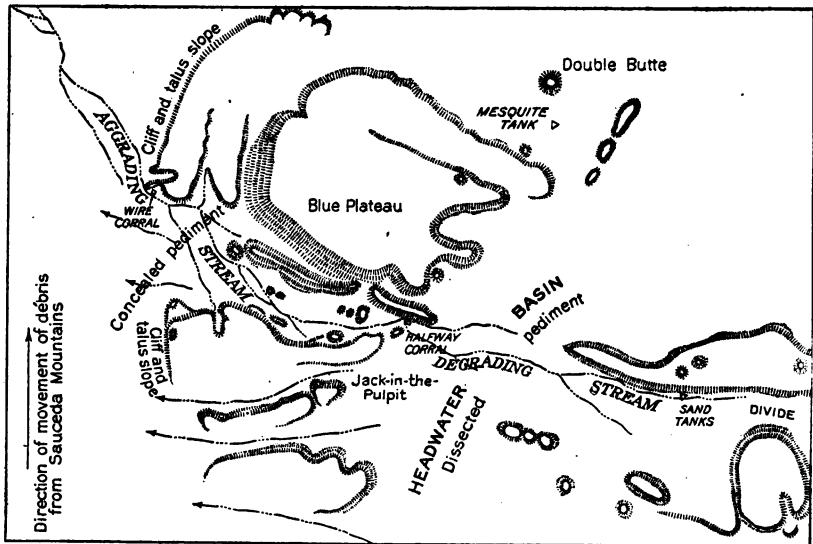


FIGURE 18.—Sketch map of the northwestern part of the Sand Tank Mountains, Ariz., showing location of dissected and concealed pediments.

will tend to unite, and eventually the range will be surrounded by a continuous pediment formed by the coalescing of many individuals. Coalescing pediments begin to be formed in the old-age stage of erosion of desert mountains, and when the projecting hills have been removed the grades will be almost stable.

DISSECTED PEDIMENTS.

If the base-level of erosion of streams flowing from the mountains is lowered, the streams carry their load of debris with ease on the increased gradient and begin to dissect the mountain pediment. Narrow canyons are cut by the streams; the canyons begin to form near the center of the basin within or on the margin of the alluvial plains and increase in length by headward erosion. As the little canyons



A. PASS WEST OF TULE TANK, ARIZ.

Niches in a granite mountain slope of the cliffy type due to massive jointing.



B. MOUNTAIN SLOPE AND DISSECTED PEDIMENT.

View north across Sand Tanks, which are in the small canyon in the foreground.



A. HEADWATER BASIN AND DISSECTED PEDIMENT IN THE SAND TANK MOUNTAINS, ARIZ.

Tilted lavas of Jack-in-the-Pulpit, on the extreme right, rest on the crystalline rocks in the foreground.



B. EAST SLOPE OF MARICOPA MOUNTAINS, ARIZ.

Undissected mountain pediment, with an outlier. In the outlier lava and gravel rest on an old erosion surface (pediment) from which the present pediment has been developed by a relatively small amount of erosion.

increase in length and complexity the pediment is carved into a maze of small hills with intervening sharply cut valleys, and the original surface is preserved only in the tops of hills or interstream areas.

Dissection of the pediment may be brought about by uplift of the mountain mass, as in the Burro Mountains, N. Mex.,⁵⁴ or the trunk stream may intrench itself and thus lower the base-level. At the north end of the Gila Mountains dissection of the narrow pediment is due to the lowering of Gila River in late Pleistocene time. Similar lowering of Santa Cruz River near its junction with Gila River has caused the dissection of alluvial fans and a very narrow pediment at the north end of the Estrella Mountains.

However, dissection of pediments due solely to lowering of a trunk stream is the exception in the Papago country; yet the pediments are commonly dissected, as shown in Plates X, A; XII, B; and XIII, A. Near or within the mountain borders each stream passes over falls or through rapids into a steep-walled canyon. The walls are rock, in many places capped with a few feet of gravel, and average about 10 feet high (Pl. XII, B). Near the mountain they may be from 20 to 150 feet high, but downstream they become lower, and near the outer border of the pediment they gradually fade out in broad plains of alluviation, as shown in figure 19.

This type of dissection of the pediment has taken place generally and irrespective of the conditions of erosion and sedimentation in the adjacent valleys. In some valleys, such as the upper part of Altar Valley, where the axial stream runs in a trench, the canyons of the pediment connect with similar canyons in the alluvial plains and with the axial trench. Dissection of the pediment in this locality may not, however, be ascribed wholly to lowering of local base-level, but the dissection of the pediment and the dissection of the valley by its axial stream are doubtless due to the same cause. In the northern part of Altar Valley there is no middle trench, yet the pediment on the northern border of the Coyote Mountains and also in the Tucson Mountains is dissected. Thus the trench of the axial stream fades out downstream, as do also the little canyons of the pediment. (See p. 73.)

The lower margin of a mountain pediment is generally mantled with the alluvium, which can be seen resting on the rock, both being dissected by the streams. This alluvium is therefore older than the undissected alluvial plains characteristic of the northern part of the Altar Valley and the interior valleys of the Papago country. What is the relation of this older alluvium to the extension of the pediment under the valley and to the original rock floor? The relations which are thought to be general in the Papago country are shown in figure

⁵⁴ Paige, Sidney, op. cit., pp. 444 et seq.

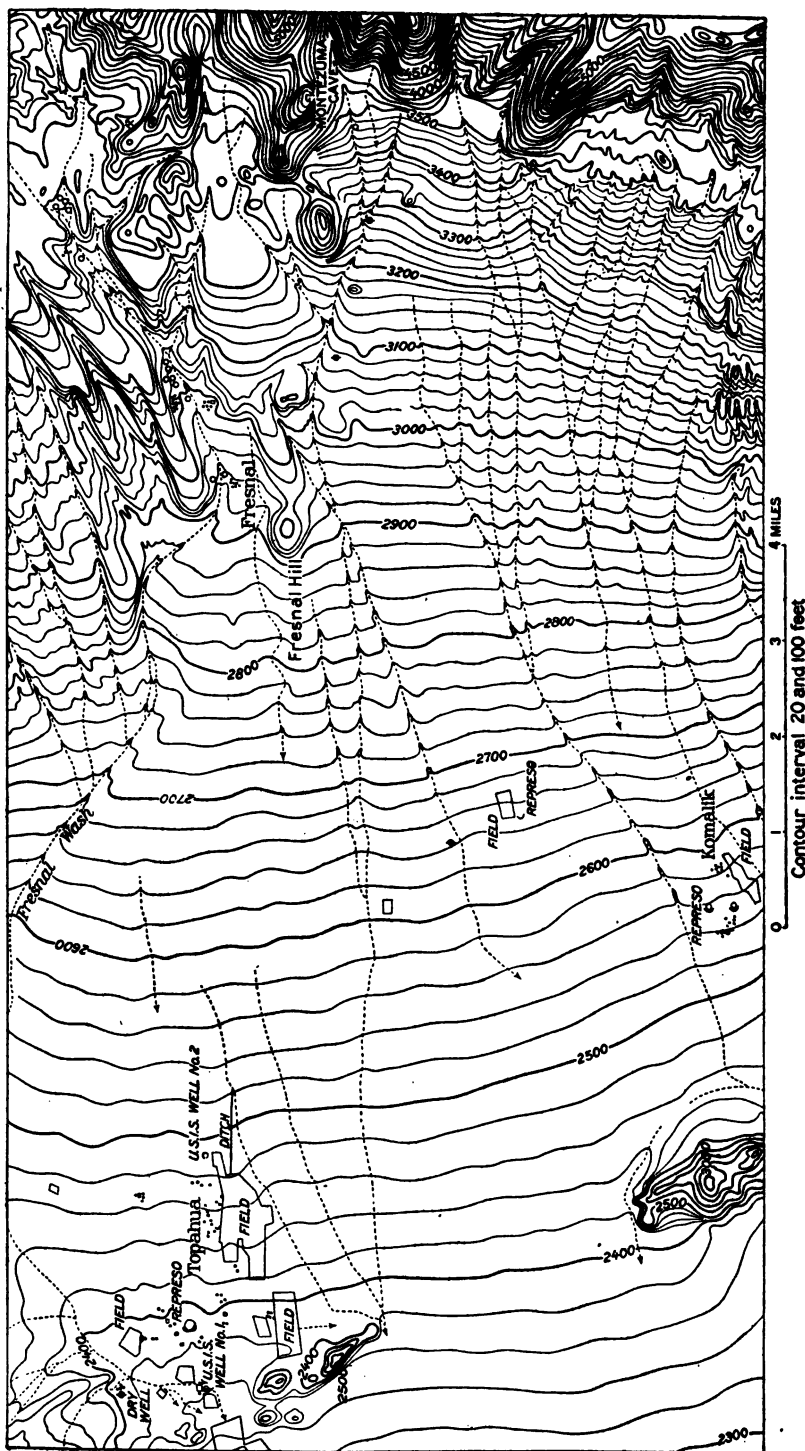


FIGURE 19.—Map of the vicinity of Fresnal and Topahua, Ariz., showing dissected pediment. Redrawn from map by the United States Indian Service.

20. It is believed that during the deposition of the older alluvium there was a gradual rise by aggradation of the middle portions of the valleys, accompanied by the erosion of a convex suballuvial bench. The alluvium then remained essentially stationary, occupying a slope of transportation of the available débris toward the local base-level. The erosion of the pediment took place during this time. The dissection of the pediment by small canyons took place after the completion of the pediment, and in that process the edges of the older alluvium were eroded, but the great mass in the middle portions of the valleys was either slightly buried or perhaps simply reworked by streams. The strict correlation of this older alluvium with that found in the valleys of Gila and Santa Cruz rivers has not been made but is discussed on page 30.

The two cross sections in figure 21 present the best data available regarding the rock floor of the valleys. Section A-B crosses the area represented in figure 14 to the Santa Rosa well, which is 920

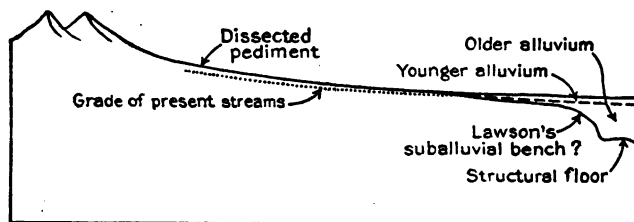


FIGURE 20.—Diagram showing the structural relations assumed for a typical valley in the Papago country, Ariz.

feet deep and does not reach the rock floor. To provide the requisite depth of alluvium at the well the rock floor under the alluvium from the edge of the pediment must be convex upward, and an error of as much as 2 miles in the location of the edge of the pediment will not vitiate this conclusion. Section C-D runs from the crest of the mountains westward across the area shown in figure 19 through the United States Indian Service wells. Well No. 2 is 602 feet deep and does not reach rock, but well No. 1 reaches rock at 100 feet. An even greater convexity of the rock floor must be assumed here, and the depression in which well No. 2 is sunk can not drain through the pass in the Artesa Mountains like the present streams.

The rock floors in both sections A-B and C-D have been drawn smoothly convex as if they were suballuvial benches, but it seems probable that their form is, in part at least, structural.

CAUSE OF DISSECTED PEDIMENTS IN THE PAPAGO COUNTRY.

Dissected pediments are widely scattered, lie at various elevations, and border valleys of unlike characteristics. The little canyons

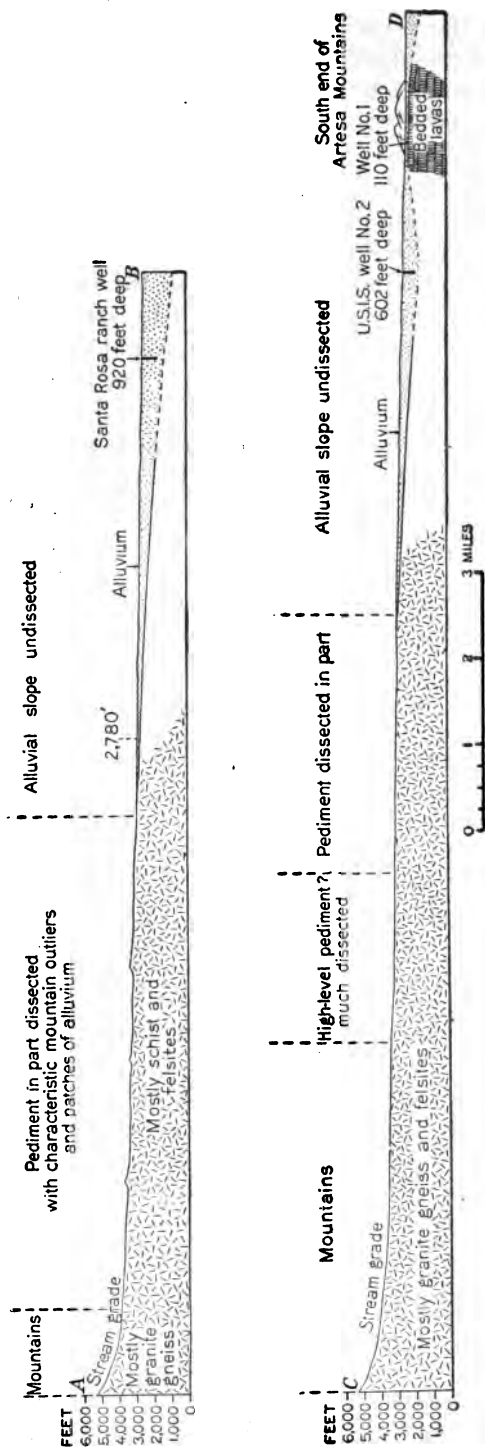


FIGURE 21.—Cross sections on the north and west sides of the Baboquivari Mountains, Ariz.

which dissect them must be due to some cause that affects the characteristics of the streams within the pediments. For a general condition a general cause must be sought, and the following analysis leads to a partial conclusion.

After the establishment of a pediment stream grades are adjusted to the supply of rock débris and the amount of water available in average floods. As the mountain front recedes there is a tendency for the slope of the pediment to become less steep as streams work farther into the mountains at the upper end; at the same time the mantle of alluvium at the lower end tends to increase in extent and still further cover the lower end of the pediment. In the interstream areas weathering and later planation tend to reduce the surface to the level of the stream beds. Conditions, however, are relatively stable.

Canyon cutting by the streams can take place only by an increase in the amount of water in proportion to the sediment carried, either by an increase in the supply

of water or by a decrease in the supply of sediment. Because the streams are wholly ephemeral, the quantity of water in them is dependent directly on the amount and rate of rainfall. On the other hand, the supply of sediment depends upon the rapidity of mechanical and chemical erosion of the rocks on the mountain slopes. The principal factor in weathering is expansion and contraction through the influence of changes in temperature. It seems improbable that any general change in temperature could be sufficiently great to make an essential difference in the daily or seasonal changes in temperature in the desert. If these changes in temperature crossed the frost line, it would, of course, make a great deal of difference whether it was colder in any period of years than it had been in the preceding period of the same length. Although freezing temperatures are common throughout the winter, it is doubtful if frost action is an effective factor in the weathering of rocks in the desert ranges. In most of the mountains the rocks do not contain sufficient moisture to make freezing temperatures of any moment in their disintegration. None of the smaller peaks appear to be affected by frost action, but in a few of the higher summits there is some evidence that frost action may aid erosion.

It seems probable, then, that the dissection of the mountain pediments at the present time is due to increased rainfall, or to a greater concentration of rainfall with consequent increased stream action. It is also probable, however, that in this region of extreme aridity minor fluctuations in climate are not recorded with great sensitiveness. The conclusion that the present state of dissection of the mountain pediment is due to increased or more concentrated rainfall does not indicate that the present is a wet period. It implies only that the last change in climate which was effective on the mountain pediments was from a somewhat dryer to a somewhat wetter period.

VALLEYS.

STRUCTURAL ORIGIN OF VALLEYS.

Between the mountains of the Papago country lie great plains or valleys. They resemble the valleys of humid regions only in that they are bounded by higher land and contain the main lines of drainage. They are actually broad plains floored with alluvial material, which rise gently to the mountains on either side. Commonly they descend in the direction of an axial stream, though some of them drain through more than one outlet. They constitute about 80 per cent of the area of the region.

In previous pages it has been shown that of the 64 mountains whose structure is partly known, 25 have been uplifted and faulted, and 21 of these have been uplifted in the same period and doubt-

less by the same process. The valleys seem to be the blocks of the earth's crust which were down-faulted at the same time that the mountain blocks were uplifted. The evidence pointing to this structural relationship is of many kinds.

The valleys are prolonged in the general direction of the mountains and in the direction of what are presumed to be the major fault lines. In many places the lavas which make the mountains or small areas of lava which are remnants of larger masses that once capped the mountains dip toward the valley. Dips of this character were observed at one or more localities in 13 valleys. In many of the valleys isolated buttes of lava stand far out from the mountains, though the mountains may have been stripped of the lava which once covered them. A well in the Valley of the Ajo struck lava at a depth of 173 feet, and a well in the valley between the Crater and Sauceda mountains found lava at 615 feet. In both places deformation, presumably accompanied by faulting, must be postulated to account for the presence of lava.

That the structural valleys may have been profoundly modified by erosion before the initiation of valley filling can not be denied. It is, however, not supported by evidence in this region.

PROCESSES OF CHANGE OPERATING IN THE VALLEYS.

The processes of change now in operation in the valleys are largely those of transportation and deposition of sediment. Erosion, which is the dominant process in the mountains and on the pediments, is inoperative in the valleys except on their borders. Thus on the edges of most pediments the alluvium is dissected by the same streams which form the little rock canyons of the pediments, and at the mouths of some of the mountain canyons, where there is no pediment, the streams are incised in the alluvium from 5 to 20 feet. The areas of dissection, however, are small. The slopes from the mountains are molded to grades determined by the amount of water in the ephemeral streams and by the supply of sediment. The wind plays a subordinate part, shifting relatively small quantities of sand from place to place.

FEATURES OF THE VALLEY FLOORS.

DRAINAGE.

In spite of the excessive aridity of the Papago country, the valleys, except the southern part of Tule Desert, drain to the sea. Part of them are tributary to the Santa Cruz-Gila system and others to Sonoita River, which reaches the Gulf of California south of the Pinacate Mountains.⁵⁵ A few of the valleys are drained by more

⁵⁵ Lumholtz, Carl, op. cit., map.

than one stream, but the typical valley is lozenge-shaped with a main stream in the axis of the lozenge, toward which the ephemeral streams from the surrounding mountains flow and the alluvial fans built by these streams slope.

AXIAL STREAMS.

The residue of the floods from the mountains that is not absorbed or evaporated on the alluvial slopes is carried off by the main or axial streams of the valleys. It is probable that there are years when the residue is insufficient to cause the water to flow out of the valley into some other valley, but when there is sufficient water it flows from valley to valley and finally into the sea. The character of these streams can best be brought out by the description of examples.

One of the longest drainage lines, though in numerous places poorly defined, runs from the Baboquivari Mountains southwestward to Sonoita River. The water from Fresnal Canyon, on the west flank of the Baboquivari Mountains (see map, Pl. IX), goes slightly northwestward through the dissected pediment and then spreads over the plain, the larger part, however, going through the gap at the south end of the Artesa Mountains and irrigating the fields of Topahua. In this part of the course there is no definite channel, the water spreading over broad flats. West of Topahua several channels branch out. The water from all of them, if sufficient, reaches Valshni Wash, which runs northwestward through Kavolik toward Tonukvo. The surface in the vicinity of Kavolik is very flat and some water probably joins Big Wash and goes directly west to join the main drain of The Great Plain north of Serventi Well. Valshni Wash almost fades out as a definite channel before reaching Tonukvo, but the larger floods undoubtedly go through to this place, whence there is a small channel and a series of smooth flats through Copeka to Quijotoa Valley, north of the Copeka Mountains. This channel becomes very indefinite but joins the equally indefinite main drain of Quijotoa Valley southwest of Hardimui. Thence indefinite channels go southward through Comovo into Comovo Valley, at the south end of which there is a well-defined channel that carries all the water which reaches this part of Quijotoa Valley past the southern point of the Mesquite Mountains. Here the water spreads and very inconspicuous channels carry it and that which drains from the west slope of the Mesquite Mountains across The Great Plain past Camote into Sonoita River. The drainage thus traced has a length from the crest of the Baboquivari Mountains to Sonoita River of about 70 miles. The times when water traverses the whole distance must be comparatively rare. Small floods probably flow down the definite channels and then spread out over the broad flats and

sink into the ground or evaporate. The continuous drainage line is probably maintained only by successive floods coming down tributaries.

One of the longest drainage lines begins with a stream which heads in granite hills east of Barajita Valley and flows about 3 miles northwestward to a narrow gap south of Walls Well. In this part of its course there is a small sandy channel which gives way in places to smooth areas of clay. From the gap and thence through Walls Well and westward for a mile or more there is a well-defined arroyo about 50 feet wide with banks 2 to 4 feet high. This channel disappears in the alluvial slopes of the Valley of the Ajo and is replaced by numerous smaller channels which lead westward toward Growler Pass. Just east of the pass is an extensive flat with clayey soils and a forest of mesquite trees, and here the small channels fade out. Two fairly definite channels flow into this flat from the southeast and northeast. By rather vague and indefinite channels in the flat the waters unite into a single channel with a gravelly bed which is about 50 feet wide and has banks from 3 to 4 feet high. This arroyo persists through Growler Pass and extends to a point about 3 miles southwest of Bates Well, where it fades out into minor channels. These channels in turn join the main wash of Growler Valley, which pursues a northwesterly course for about 30 miles to the Mesquital, an adobe flat that is similar to the one east of Growler Pass and that lies southeast of the southern point of the Aguila Mountains. From the Mesquital a channel leads to the axial stream of San Cristobal Valley. This axial stream has a well-defined channel about 50 feet wide trending northwestward, but near Garcia Well it fades out into an adobe flat which gradually increases in width until 9 miles farther on, at the Southern Pacific Railroad, it is almost 2 miles wide. Around the borders of the flat are low bluffs which are 2 to 5 feet high near Garcia Well and increase to 20 feet in height near the railroad. In this flat the channels are very small, but at the railroad a channel about 20 feet wide and 3 to 4 feet deep begins, which increases in width and depth until it reaches the flood plain of Gila River.

TRIBUTARY STREAMS.

The tributary streams that discharge into the axial streams are all of the ephemeral type and are active only during or immediately after rains. Near the mountains they commonly run in well-defined channels; farther down the slope they divide into several channels or spread out into broad sheets.

McGee has recorded in great detail a sheet flood which he observed in 1894 on one of the tributaries of Santa Cruz River. This tributary rises in the Santa Rita Mountains, crosses the dissected pedi-

ment and the dissected alluvial slope, and joins the flood plain of the Santa Cruz on a broad, smoothly sloping plain with a grade of 150 feet to the mile. McGee's description,⁵⁶ somewhat condensed, follows:

During the 1894 expedition a moderate local rain occurred. The rainfall was perhaps one-fifth of an inch, sufficient to moisten the dry ground, and was probably greater in the adjacent foothills of Santa Rita Range. Within half an hour a roar was heard in the foothills, rapidly increasing in volume; the teamster set out along the road up the [Santa Cruz] valley at best speed; but before he had gone 100 yards the flood was about him. The water was thick with mud, slimy with foam, loaded with twigs, dead leaflets, and other flotsam; it was seen up and down the road in either direction, fully half a mile in all, covering the entire surface save a few islands protected by exceptionally large mesquite clumps. The torrent advanced at race-horse speed at first, but, slowing rapidly, died out in irregular lobes not more than a quarter of a mile below [west of] the road; yet, though so broad and tumultuous, it was nowhere more than about 18 inches, and generally only 8 to 12 inches, in depth. The front of the flood was commonly a low, lobate wall of water 6 to 12 inches high, and it was evident that most of the water first touching the earth as the wave advanced was immediately absorbed and as quickly replaced by the oncoming torrent rushing over previously wetted ground. Such were the conspicuous features of the sheet flood—a thick film of muddy slime rolling viscously over a gently sloping plain; and this film was a transformed stream still roaring through a rugged barranca [canyon] only a few miles away. For perhaps five minutes the sheet flood maintained its vigor and even seemed to augment in volume; the next five minutes it held its own in the interior, though the advance of the frontal wave slackened and at length ceased, and in half an hour from the advent of the flood the ground was again whitening in the sun, save in a few depressions where muddy puddles still lingered.

The after effects of the flood were the accumulation of flotsam against the upper sides of clumps of shrubbery, ant hills, and ground-squirrel mounds; from these the limits of the flood could be traced, showing that it nearly blended with other similar floods from neighboring barrancas and arroyos. A less striking effect was the accumulation of a nearly continuous film of sediment, chiefly fine sand or silt. This film was usually an inch or less in thickness, though sometimes it lined depressions to depths of several inches.

Floods of the type described seem to be normal to the region. On the upper parts of the alluvial slope they flow in linked and shifting channels, but farther down, where they have dropped all the coarse sediment and are carrying only sand and mud, they spread out in broad sheets. Concentration of these sheets by permanent or temporary obstacles may cause the formation of a channel, but many of these channels are discontinuous, and there are broad flats without channels.

ADOBE FLATS.

The broad flats that are formed by deposition from sheet floods are floored with sandy clay or, in local parlance, adobe. Hence they are called adobe flats.

⁵⁶ McGee, W J, Sheet-flood erosion: Geol. Soc. America Bull., vol. 8, pp. 100-101, 1897.

The channels in the flats are of two types—shallow sandy channels ordinarily 2 to 5 feet wide and 3 inches to a foot deep, and deep channels from 5 to 6 feet deep and 15 to 30 feet wide. Parts of these larger channels may have a clay bottom and hold water for a time after rains or floods. Other shallow basins or pans, apparently produced largely by the trampling of animals, also hold water, and these two types of pools are called charcos.⁵⁷

Orchard-like forests of mesquite are common on adobe flats. Usually the trees grow along the channels, and not uncommonly these lines of trees are paralleled by similar lines of dead or dying trees that mark the position of channels which have now disappeared. The adobe flats of Vekol Valley, however, are bare of trees and are covered by hummocks of "galleta" grass. Scraggly bushes of mesquite and unusually large creosote bushes separate the grassy adobe flat from the alluvial slope covered by vegetation of the normal type, dominated by the creosote bush.

Adobe flats are of all sizes. Many small ones 30 to 40 feet wide and a few hundred feet long occur along streams otherwise marked by channels. Others cover square miles of country and when flooded are gently moving sheets of water. The surface when dry is normally hard and smooth and somewhat streaked in appearance owing to the presence of fine crenulations in the direction of flow. There are also bits of rubbish collected on the upstream side of every obstruction.

PLAYAS.

The only temporary lake in the region lies on the international boundary and receives the drainage of the southern part of Tule Desert. The locality is called Las Playas, and the bed of the temporary lake is a good example of a playa, a flat area occasionally flooded by water which stands and evaporates. The surface is crossed by mud cracks which break the dark clay soil into large blocks. Many of the cracks are 3 to 4 inches wide at the surface and extend downward at least 3 feet. The edge of the barren flat is marked by scrubby mesquite bushes clustered about the charcos and channels that occur at the places of entrance of tributary streams.

WIND DEPOSITS.

In the area west of Ajo, on the whole the driest part of the region, wind-blown sand is fairly common. The Yuma Desert is almost completely mantled with sand from 1 to 10 feet deep. The presence of grass and bushes and the general shapelessness of the dunes indicate that the movement of sand is not rapid. The eastern margin of the Yuma Desert and the west side of the Gila Mountains are

⁵⁷ Bryan, Kirk, Origin of rock tanks and charcos: *Am. Jour. Sci.*, 4th ser., vol. 50, pp. 203-206, 1920.

drained by a stream flowing northward to Gila River, and along this stream erosion is sufficiently active to prevent the deposition of sand.

In the flood plain of Gila River there are many groups of low dunes, composed of sand derived from the broad sandy river channels. These dunes are commonly fixed in position by clumps of mesquite.

Along the eastern margin of the Lechuguilla Desert, Tule Desert, and Mohawk Valley are belts of sand dunes, which appear to be the residue of sand accumulated by the winds after sweeping the entire width of the valleys. The belt of dunes is particularly conspicuous at the southern end of the Pinta Mountains. In this locality the dunes are invading the mouths of the mountain canyons and impeding stream erosion. A belt of wind-blown sand from a quarter of a mile to a mile wide surrounds the Pinacate plain. Growler Valley and the Valley of the Ajo are almost free of wind-blown sand, but patches of drifted sand occur on the Sentinel plain and around its margin.

In the Quijotoa Valley, The Great Plain, and the plain near Copeka there are areas of wind-blown sand. The sand is usually only from a few inches to 4 feet thick and lies on the clayey surface of extensive adobe flats. The irregular distribution of the sand impedes the drainage and helps to break up and spread the floods. In making the artificial ponds of Tonukvo, Copeka, Comovo, and Camote the Papago Indians have taken advantage of the partial damming of channels in the adobe flats by wind-blown sand.

Interference with stream channels is perhaps the most notable effect of wind work in this region. In many localities channels in which water ran six months or a year before are blocked by low dams of wind-blown sand from 6 inches to a foot high. The next flood will probably take a new course, which will in turn be blocked. Thus the wind assists in the further diversion of streams which are already likely to be diverted under the laws of stream action.

TERRACES.

Many of the streams of the Papago country now flow below the level of deposits which they have laid down in past time. They flow in trenches bordered by bluffs leading to a broad terrace which, conforming to the grade of the alluvial slope, extends to the mountains. Some streams have deposited material at more than one level and thus are bordered by several terraces.

TERRACES OF GILA RIVER.

The valley of Gila River contains many terraces which parallel the river. The highest terrace is represented only in a few locali-

ties by small benches or by the tops of isolated hills and is composed of the material already described as older alluvium (p. 29). The lower terrace is well developed along the whole length of the river and is bounded on the lower side by bluffs about 75 feet high. It is composed of alluvium deposited in part by the river itself and in part by side wash from the ephemeral tributaries of the river. This material is referred to as the younger alluvium (p. 30). Below the terrace is the flood plain of the river, with its Recent deposits. These relations were recognized by Lee,⁵⁸ who correlated the alluvium of the higher terrace with similar material on Colorado River, which he called the Temple Bar conglomerate,⁵⁹ and the lower terrace would thus be the equivalent of the Chemehuevis gravel of the same river. The older alluvium, which corresponds perhaps to only a part of the Temple-Bar conglomerate, lies at various elevations and is tilted in a number of localities, as at the north end of the Gila Mountains, 5 miles north of Blaisdell, south of Wellton, and in Tonto Basin.⁶⁰ Near Mesa a well 1,305 feet deep penetrates only alluvium and shows that the valley fill extends more than 100 feet below sea level.⁶² As Gila River could not excavate a valley below sea level, earth movements must have followed the deposition of the older alluvium. Doubtless to these movements and the subsequent extensive erosion may be attributed the small areas now covered by the older alluvium and the inequality in height of the several outcrops. Field work in San Pedro Valley in 1920 and 1921 indicates that a large part of the deeper valley fill is of Tertiary age and older than the older alluvium.

The younger alluvium, of Chemehuevis age, forms a well-defined terrace and indicates that in Pleistocene time the river filled its valley to a level about 75 feet above its present elevation. The data for the age of the younger alluvium are presented on page 30.

Since that time the river has cut a valley through the deposits of Chemehuevis age and is again depositing material on its flood plain. Early reports indicate that up to about 1880 the Gila flowed in a relatively deep channel through its flood plain, overflowing it only in times of flood. There was also a considerable low-water flow. At present the channel is a sandy waste with many tortuous subsidiary channels, constantly shifting in position, and there is no low-water

⁵⁸ Lee, W. T., *Underground waters of Salt River valley, Ariz.* : U. S. Geol. Survey Water-Supply Paper 136, p. 112, 1905.

⁵⁹ Lee, W. T., *Geologic reconnaissance of a part of western Arizona* : U. S. Geol. Survey Bull. 352, p. 18, 1908.

⁶⁰ Lee, W. T., *Underground waters of Salt River valley, Ariz.* : U. S. Geol. Survey Water-Supply Paper 136, p. 112, 1905.

⁶² Lee, W. T., *op. cit.*, p. 115. Additional evidence from well records is given by Ross, C. P., *The lower Gila region, Ariz.* : U. S. Geol. Survey Water-Supply Paper — (in preparation).

flow except in favored places. There seems to be a greater proportionate load of sediment, which under present conditions is silting up the channel.

TERRACES OF ALTAR AND SANTA CRUZ VALLEYS.

Santa Cruz Valley and its tributary, Altar Valley, which lies parallel to and west of it, are marked by several common features. Altar Valley lies between the Baboquivari and Coyote mountains on the west and the Tumacacori, Cerro Colorado, Sierrita, and Tucson mountains on the east and drains north to Abra Valley and thence to the Santa Cruz. It is about 40 miles long and ranges in width from 8 to 15 miles. The head of the valley from Buenos Aires south, and for 3 to 4 miles out from the mountains on the west side as far north as Las Moras and on the east side as far north as the San Luis ranch, is a plain cut on rock—a mountain pediment. About 4 miles south of Buenos Aires is the divide which separates the drainage going south past Sasabe into Mexico. It is smooth and flat. The head of the valley consists of confluent pediments formed by streams from the adjacent mountains, some of which flow north and others south.

Pediments border the east side of the valley and are probably extensive. On the west, however, from Las Moras to the Coyote Mountains, the pediment is narrow and the plains are covered by very coarse alluvium. Along the Coyote Mountains the exposed pediment is from half a mile to 3 miles wide.

The headwater streams in the pediment areas are incised in narrow valleys from 10 to 50 feet deep. These trenches lead from all the mountain canyons to an axial stream which, originating in the union of Arivaca Creek and the stream which follows San Luis Canyon, runs north almost to the Anvil ranch. Each trench is a flat-bottomed valley from a quarter of a mile to $1\frac{1}{2}$ miles wide. The loamy bottom is marked by a well-defined arroyo with banks from 2 to 6 feet in height. The bluffs of the trench have their maximum height of about 75 feet near Buenos Aires, decreasing in height upstream and downstream. Near the Anvil ranch the bluffs are about 20 feet high, and thence northward they fade out rapidly, so that at the Robles ranch there is no sharp separation between the plain of alluviation of the main stream and those of its tributaries.

The trench of the main or axial stream shows no definite terrace, but a terrace is common on the tributaries, though owing to the "accidents" of erosion it is absent in many places. West of Pozo Nuevo the tributary valleys are from a quarter to half a mile wide. Each valley has a flood plain in which the stream is intrenched about

10 feet, like the axial stream. Above the flood plain is a terrace about 15 feet high, and then a narrow flat, followed by a gentle slope to the level of the plains, 35 to 40 feet higher.

Near Arivaca the flood plain of Arivaca Creek is bounded by low bluffs about 20 feet high which constitute the face of a narrow discontinuous terrace. About 40 or 50 feet above the terrace lies a rolling plain cut on rock, which is part of a well-developed mountain pediment. Arivaca Creek near the town now runs in a trench about 200 yards wide and 15 feet deep. This trench has been formed within recent time, for when white men first came into the country the flood plain was a marshy flat. Lieut. Michler⁶⁴ visited Arivaca in July, 1855, and his narrative states that "numerous springs lie concealed among the tule," a phraseology which implies that there was a swamp with rushes or "tule" at this locality.

Santa Cruz River rises in Arizona at the southern base of the Canelo Hills and flows southward through a broad depression called

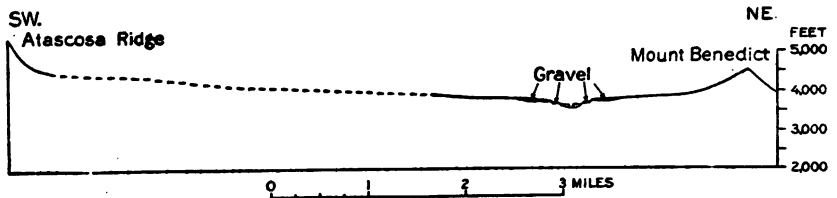


FIGURE 22.—Cross section of part of Santa Cruz Valley (Nogales Wash), Ariz., from Mount Benedict to the Tumacacori Mountains.

the San Rafael Valley, between the Patagonia and Huachuca mountains. Crossing the international boundary, the river describes a loop of 30 miles and reenters the United States 6 miles east of Nogales. At the international boundary the stream has an elevation of about 3,700 feet and thence northeastward to Calabasas its grade is 40 feet to the mile. Near Calabasas the Santa Cruz is joined by Nogales Wash, sometimes called Potrero Creek, which flows northward from Nogales, and by Sonoita Creek, which heads on the east side of the Santa Rita and Patagonia mountains. This part of the Santa Cruz Valley is a broad lowland about 17 miles wide from the base of the Patagonia Mountains to Atascosa Ridge, in the Tumacacori Mountains. The lowland is composed of long ridges and flat-topped spurs extending from the bordering mountains toward Santa Cruz River and its tributaries. Similar ridges slope from the divide between Nogales Wash and the river. The culminating point of this divide is Mount Benedict, a bold, somewhat conical mountain. Between the ridges are sharp-walled, terraced canyons, which

⁶⁴ Emory, W. H., Report on the United States and Mexican Boundary Survey, vol. 1, p. 119, 1857.

lead to the flat inner valleys along Santa Cruz River and its two main tributaries. The flat floor of Nogales Wash is from an eighth to half a mile wide, a moist and fertile meadowland which narrows in places but grows wider downstream until it merges into the similar floors of the inner valleys of Santa Cruz River and Sonoita Creek. In these flat meadows the streams have cut narrow, steep-sided gullies from 10 to 30 feet deep.

The bluffs bordering these flood plains show a double terrace, the upper one coincident with the sloping ridges and the lower about 50 feet above the flood plains. These relations are shown in figure 22.



FIGURE 23.—Cross section of Santa Cruz Valley from Sardina Peak to the Santa Rita Mountains near Tubac, Ariz.

The upper terrace is in places covered with thin alluvium. The lower terrace is everywhere capped with 10 to 20 feet of gravel.

From Calabasas to the mouth of Sopori Creek, Santa Cruz Valley is from 8 to 12 miles wide. Long-dissected slopes lead down to an inner valley bounded by bluffs. Near the mountains the side streams flow in deep gorges through narrow pediments, and lower down they occupy flat-bottomed valleys bounded by bluffs of alluvium. The floors of the tributaries join and merge with the flood plain of Santa Cruz River. This flood plain is 1 to 2 miles wide, and through it

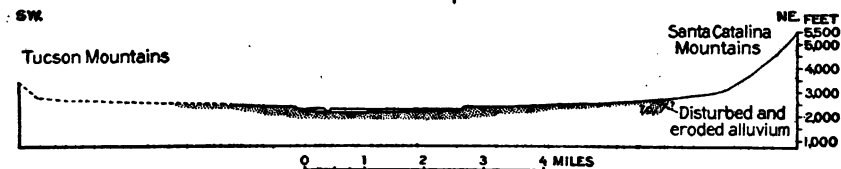


FIGURE 24.—Cross section of Santa Cruz Valley at Jaynes, Ariz.

the stream flows in a steep-walled channel from 10 to 20 feet deep. The cross section in figure 23 shows the character of the slopes and the form of the inner valley near Tubac, a location typical of this portion of the valley. The cross section brings out the double terracing of the valley, but these terraces, though of approximately the same height as those farther upstream, are unlike them in being composed wholly of alluvium.

Forty miles to the north, near Tucson, the inner valley, with its flood plain and the narrow trench in which the river runs, is bounded by ragged bluffs about 25 feet high, as shown in figure 24. From the tops of these bluffs the alluvial slopes sweep upward to the mountains.

There is no second terrace, but vague irregularities in these slopes look like the remnants of an older valley filling, and were so interpreted by Huntington.⁶⁵

From Tucson northward the bluffs bounding the inner valley of the river decrease in height and near the north end of the Tucson Mountains disappear. Similarly, the trench in the flood plain becomes shallower, and Santa Cruz River in flood spreads widely over great adobe flats in which the main channel is so obscure that its mapping is arbitrary. Figure 25 is a cross section through Toltec, where the river has two main channels, which are, however, very shallow and seldom hold all the flood waters. The great flats of Santa Cruz River merge with those of its tributaries. The stream that drains Altar and Abra valleys has, like the others, lost the terracing characteristic of its headwaters. The flats of Santa Cruz River lie at or only slightly above the level of the bluffs along Gila River, which are about 50 feet high in the stretch from Florence to Gila Crossing. The flats were evidently developed when Gila River flowed at the level of these bluffs. The lowering of Gila River has

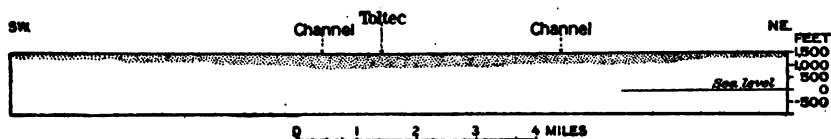


FIGURE 25.—Cross section of Santa Cruz Valley near Toltec, Ariz.

affected its tributary in its lower portion only, where for a distance of 5 or 6 miles upstream from the junction near Gila Crossing Santa Cruz River lies in a shallow valley 10 to 50 feet below the surrounding plain.

The physiographic features of Santa Cruz River, just recounted, are similar to those of Altar Valley. From Calabasas southward the Santa Cruz Valley and its tributary valleys consist of dissected pediments sloping from the bordering mountains to a terraced inner valley. The topography is similar to that near Arivaca and in the southern part of Altar Valley. The events recorded by this topography seem to be (1) long-continued erosion following the original uplift of the mountains and forming extensive mountain pediments; (2) deposition of alluvium on the lower portions of the pediments in a period of deposition either following the first period of erosion or concurrent with it; (3) erosion of an inner trench at the level of the terrace, shallower but wider than the present trench; (4) deposition on the floor of this trench in a second period of deposition either following the second period of erosion or concurrent

⁶⁵ Huntington, Ellsworth, *The climatic factor*: Carnegie Inst. Washington Pub. 192, p. 24, 1914.

with it; (5) erosion of the inner valley to a depth slightly below the flood plain; (6) deposition of the silt and sand of the flood plain in a third period of deposition either following the third period of erosion or concurrent with it; (7) erosion of the trench or channel in the flood plain. The last event has taken place within historic time and is discussed more fully in a later paragraph.

The cross section at Tubac resembles the part of Altar Valley near Secundino Well, where the bluffs of the inner valley are of alluvium. The terrace, however, is not well developed in Altar Valley except in certain tributary streams. (See p. 73.) The events recorded are similar in sequence to those recorded farther south and fall into seven stages, but deposition has been far more important than erosion, especially in the earlier stages.

The cross section near Tucson (fig. 24) probably indicates the same sequence of events, but the reddish faulted and eroded alluvium near the mountains can not be correlated with the alluvium capping the dissected pediments near Calabasas or the great body of alluvium of the dissected alluvial slopes near Tubac, as it is doubtless of Tertiary age. The alluvium of the sloping plains and terraces can not be separated into an older and a younger division without further field work.

The cross section near Toltec (fig. 25) shows deposition only, and the Santa Cruz Valley in this part of its course resembles Altar Valley at the Robles ranch. Not even the recent channel trench persists into the Santa Cruz flats, and the history of this part of the Santa Cruz Valley, so far as it is recorded in the surface features, is one of uninterrupted deposition.

The recency of the cutting of the channel trench of Santa Cruz River in the stretch between Calabasas and Tucson was first pointed out by Spaulding⁶⁶ and has been studied in detail by Huntington.⁶⁷ According to the testimony of local residents, the flood plain was once covered with sacaton grass, the channel of the river was insignificant, water during floods spread over most of the grassy flood plain, and tules (bulrushes) grew in the boggy places. Late in the eighties ditches and cattle trails were enlarged by floods and the present channel, which is from 100 to 300 feet wide and from 12 to 15 feet deep at Tucson, was made. The great floods of 1905 completed the channel, and Huntington thinks that since that time there has been a tendency for the channel to silt up.⁶⁸ Near Point of Rocks, north of Tucson, Huntington found palo verde trees (prob-

⁶⁶ Spaulding, V. M., *Distribution and movements of desert plants*: Carnegie Inst. Washington Pub. 113, p. 9, 1909.

⁶⁷ Huntington, Ellsworth, op. cit., pp. 33-34.

⁶⁸ Idem, pp. 24, 33.

ably *Cercidium torreyanum*) whose lower trunks were buried in alluvium and reexcavated by the cutting of the channel. On cutting down one of these trees and examining its rings of annual growth he found that it began to grow between the years 1670 and 1680 on a plain about 5 feet below the level of the flood plain of 1880. Gradual deposition of silt buried the base of the tree during the next 200 years.⁶⁹

Father Kino's account of the valley near Tucson is of course colored by his enthusiasm and missionary zeal, but his statements imply conditions very unlike those of the present. In 1692 he found 800 persons at San Xavier del Bac, 12 miles south of Tucson.⁷⁰ In January, 1697, there were at the same place "beginnings of good sowings and harvests of wheat," and in November of the same year he counted in the ranchería and environs 6,000 persons and "found even bread, fresh and very good."⁷¹ In October, 1699, he counted 1,000 persons in the ranchería of San Xavier del Bac and states: "The fields and lands for sowing were so extensive and supplied with so many irrigation ditches running along the ground that the father visitor [Antonio Leal] said they were sufficient for another city like Mexico."⁷² Of San Cosme del Tucson, probably located just west of the present city of Tucson, he says that it had "splendid fields." Similarly he states that he counted 200 men representing 200 families at San Agustín del Oyaut (Oiaur), probably between Jaynes and Rillito. At Santa Catarina del Cuytoabagum he found 300 men representing 300 families.⁷³ This ranchería was probably near the present Picacho. In April, 1700, after erecting the foundation of a church and beginning a mission at San Xavier del Bac, Kino states that the mission "will be able to have throughout the year all the water it may need, running to any place or workroom one may please, and one of the greatest and best fields in all Nueva Biscaya."⁷⁴

The purport of these statements is that at the beginning of the eighteenth century, about 20 years after the palo verde which Huntington examined had sprouted, the flood plain of Santa Cruz River was without a deep channel and had a permanent stream, else the Indians with their primitive wooden tools would not have been able to divert the water into ditches, nor would the water have lasted all the year. It should be remembered also that the cutting of the channel trench has facilitated the flow of ground water at the present time. There must, then, have been much more water available in 1700 to cause the river to flow the year round. The extensive settle-

⁶⁹ Huntington, Ellsworth, op. cit., pp. 33, 34.

⁷⁰ Bolton, H. E., Kino's historical memoir of Pimería Alta, vol. 1, p. 122, Cleveland, 1919.

⁷¹ Idem, p. 173.

⁷² Idem, p. 205.

⁷³ Idem, p. 206.

⁷⁴ Idem, p. 236.

ments down the river from Tucson are also significant, for, unless the floods were stronger and more frequent than now, 200 families could not live by primitive agriculture between Jaynes and Rillito, nor could 300 families live near Picacho. The narrative of Kino thus adds force to the arguments of Huntington that there was once a wetter climate in southern Arizona. One of these periods of slightly wetter climate appears to have been during the time of the missionaries. The first effect on topography of a change to drier conditions came between 1880 and 1890, when changes in the channels of streams took place in widely scattered localities in the Southwest. In northern Arizona Gregory⁷⁵ has been able to fix the dates when a number of streams began to cut trenches. These dates range from 1880 to 1894, but the most extensive work was done late in the eighties. Lumholtz⁷⁶ states, on the authority of Señor Isauro Quiroz, a resident of Sonoita, that the recent changes in Sonoita River took place on the night of August 6, 1891. Before that time the head of permanent water in the river was in a narrow channel, above which were extensive swamps (ciénagas) for about 3 miles. The present channel, which in 1912 was 250 feet wide and from 18 to 20 feet deep, formed suddenly after a heavy rain. The swamps were drained, and a forest of mesquite sprang up. Many metates, manos, and sea-shell ornaments were found by local people after the cutting of this channel, which, according to the location pointed out by Señor Quiroz, must have been buried at least 20 feet below the surface of the flood plain. Lumholtz found one metate embedded in the embankment about 12 feet below the surface. There is, then, good evidence that there were considerable meadows and ciénagas at Sonoita, where Indians lived for a very long time, during which there was a filling of silt to a depth of 20 feet. This accords with the following statements made by Father Kino⁷⁷ in October, 1700:

This post and rancharía of San Marcelo [del Sonoydag] is the best there is on this coast. It has fertile land, with irrigation ditches for good crops, water which runs all the year, good pasture for cattle, and everything necessary for a good settlement, for it has very near here more than a thousand souls, and many more in its environs.

The significant part of this statement is the number of people "very near here," for at present the whole valley of the Sonoita will not support more than a fifth as many. Lumholtz says that in 1912 there were in this valley 100 Mexicans and 70 to 80 Indians.⁷⁸ Even with the benefits of domestic animals, wheat, fruit trees, and other

⁷⁵ Gregory, H. E., *Geology of the Navajo country, Ariz.*: U. S. Geol. Survey Prof. Paper 93, pp. 130-131, 1917.

⁷⁶ Lumholtz, Carl, *New trails in Mexico*, pp. 178-180, 1912.

⁷⁷ Bolton, H. E., *op. cit.*, p. 255.

⁷⁸ Lumholtz, Carl, *op. cit.*, pp. 176, 387.

facilities which were unknown before Kino's time, it is doubtful if more than 300 people have lived in the Sonoita Valley in recent years.

Similar changes in conditions have been widespread in the Southwest. Old-timers tell of "cutting hay with a hoe" and riding in grass "stirrup high" during the seventies on the "mesa" east of Albuquerque, in central New Mexico. These tales are in marked contrast to conditions since 1900, with which the writer is familiar. The valley of the Rio Puerco (of the East) west of Albuquerque has had a history like that of the Santa Cruz. Once the stream had a channel only 2 or 3 feet deep and during great floods spread over its flood plain, which ranges in width from a quarter of a mile to a mile. The Spaniards drove the Navajos out of the valley and founded the towns of San Ignacio, San Fernando y Blas, and San Francisco on the tract of land now known as the Bernabe M. Montaña grant. Water was diverted by low brush dams from the river to acequias for irrigation. Large floods gave a natural irrigation to the crops. According to local residents, the cutting of the present channel trench, which is from 25 to 30 feet deep and from 200 to 300 feet wide, began in the eighties. The cut progressed upstream by headward erosion and thus successively cut off the ditches from access to the stream. The violent floods flowed in the deep channel, no longer covering the flood plain, and they also prevented the building of adequate diversion dams, so that the towns were gradually abandoned. San Ignacio persisted longer than the others. The inhabitants could not carry on agriculture, except for a little precarious flood-water farming, but were supported by trade, stock raising, and freight hauling.

These scattered records indicate that before 1880 the streams of the arid Southwest and of Arizona in particular were largely engaged in depositing sediment, and many flood plains were grassy or swampy. Erosion began during the eighties and has continued to the present time. Somewhat different features are presented by Gila River (p. 71), on which the change in regimen coincides in time with the changes on Santa Cruz River but differs in character.

TERRACES IN THE INTERIOR VALLEYS.

Pumpelly⁷⁹ was the first to observe that the valleys west of the Baboquivari Mountains are undissected compared to those east of these mountains. The dissection of the pediments and the upper parts of the alluvial slopes has already been mentioned (pp. 62, 66). Vekol Valley, however, presents some anomalous features. The main stream, after passing through extensive flats covered with

⁷⁹ Pumpelly, Raphael, *Mineralogical sketch of the silver mines of Arizona*: California Acad. Sci. Proc., vol. 2, pp. 127-139, 1863.

"galleta" grass where deposition is going on, enters, near the Brush Corral, a shallow trench. The trench is from 5 to 10 feet below the adjacent slopes and is from 100 to 300 feet wide. The floor of the trench is formed of a deep loamy or sandy clay soil and supports a thicket of large mesquite trees. The stream is still further intrenched in a channel trench from 5 to 10 feet deep and apparently no longer covers the plain in time of flood. This arrangement of slightly dissected alluvial slopes, low bluffs flanking a flood plain, and a channel trench continues northward for about 10 miles and then fades out, so that at Mobile, on the Southern Pacific Railroad, 18 miles farther north, the stream has several channels, none of which are well marked. In miniature, then, there is reproduced on this stream the physiography of the Santa Cruz at Tucson, and in similar fashion the terraces fade out downstream.

Somewhat similar but vaguer terraces were observed on the stream that drains the southern part of Barajita Valley. A gravel-covered hill about 10 feet high, which gives the name to Charco de la Lomita, and similar hills near Totobit Tanks and at other localities may be vestiges of terraces of a like kind now destroyed or largely buried in the present cycle of sedimentation in the interior valleys.

GEOLOGIC AND PHYSIOGRAPHIC HISTORY.

PRE-TERTIARY EPISODES.

The geologic history of the Papago country begins in the obscurity of early pre-Cambrian time. As in other parts of Arizona, sedimentation, now represented by schists, was followed by igneous intrusion of granitic rocks, accompanied by intense dynamic metamorphism. Then followed a long period of erosion, which, so far as the evidence goes, continued to the beginning of Cambrian time. The later pre-Cambrian, known from the Grand Canyon⁸⁰ region, has not yet been differentiated in the Papago country and may be absent.

Paleozoic time seems to have been an era of quiet in respect to earth movements, with spreading seas which lapped over the region from the southeast. The expansion of the sea from the southeast is recorded by the occurrence of Cambrian, Devonian, and Carboniferous rocks in the Santa Rita Mountains and of Cambrian and Carboniferous rocks in the Tucson Mountains, but in general west of Santa Cruz River only Pennsylvanian rocks have been found. The absence of Paleozoic rocks from the region west of Ajo and from the lower Gila region seems to imply either that these regions remained above the

⁸⁰ Noble, L. F., The Shinumo quadrangle, Grand Canyon district, Ariz.: U. S. Geol. Survey Bull. 549, pp. 37-60, 1914.

Paleozoic seas or that they were particularly affected during the succeeding revolution, when folding took place in the ranges east of Santa Cruz River.

Early Mesozoic time was in other parts of Arizona marked by the deposition of continental deposits, many of them indicating arid conditions. No sedimentary record is available in the Papago country except in the Tucson Mountains, but the Paleozoic rocks were dislocated and large parts of them removed before the Mesozoic igneous intrusions took place. The igneous activity of Mesozoic time included extrusion of lava and intrusion of large batholithic masses. Hardly had this activity ceased when deposition by streams began. The area of deposition, however, covered only the southeastern part of the region toward the early Cretaceous sea. In this area folding and overthrusting took place in post-Cretaceous time. The Papago country may also have been involved in these movements, but continuous erosion down to Tertiary time has largely obliterated the evidence.

TERTIARY LANDSCAPE.

The Tertiary history of the region is striking in character and represented by a profusion of rocks. The details of this history can not be given, however, for lack of evidence. Three glimpses of the region during this period are revealed.

At the beginning of Tertiary time uplift and erosion began and the major features of the present time were rudely blocked out. It is not likely that this uplift was simultaneous over the whole area, but the present high land seems to have been elevated, and deposition by streams took place in local basins.

Of the deposits of Tertiary time, the beds in Adobe Canyon, in the Santa Rita Mountains, are definitely known to be Eocene. The other Tertiary sedimentary rocks can not be definitely dated, but they testify to the climatic and physiographic conditions of the time. All the beds are arkosic—that is, they are composed in part of undecomposed grains of feldspar. Rudely bedded, unsorted, in places with large boulders, they must have been laid down by torrential, probably ephemeral streams under climatic conditions very similar to those of the present day. They commonly rest on the eroded surface of the underlying rocks, and the basal beds are made up largely of material derived from local sources. The beds consist of the coarse detritus derived from the erosion of desert mountains, laid down on the flanks of these mountains. The succeeding lava flows extended, in places, over the Tertiary conglomerates and usually far beyond them, covering the mountains in whole or in part. As uplifted and exposed by erosion, the surface on which the con-

glomerates and volcanic rocks rest is in many places smooth, but protuberances stand from a few feet to as much as 1,500 feet above the general level. The elevations were low residual mountains of the sierra type, surrounded by pediments leading down to the basins in which the conglomerates had accumulated. The end of the Tertiary volcanic period found this topography masked by lavas accumulated to maximum thicknesses of 2,000 feet.

Much more work will be necessary to determine the areas that were once covered by lava. In the central part of the region the lavas were almost continuous, and the district including the Sand Tank, Saucedá, Ajo, and Growler mountains seems to have been one of the great lava fields of Tertiary time. In other localities, such as the Maricopa and Salt River mountains (p. 27), the lavas were thin, and probably there were some areas without lava.

Between the areas of accumulation of lavas were doubtless basins in which streams deposited the gravel now found interbedded with the lavas. Farther north, in the lower Gila region, there were brackish waters in which limestone was deposited.⁸²

The third glimpse of Tertiary time shows the region after the period of faulting, in which great strips and blocks of the earth's crust had been uplifted and tilted to form the present mountains and similar blocks and strips had been relatively depressed to form the valleys. These movements probably took place in or at the end of Pliocene time.

PLEISTOCENE AND RECENT TIME.

The later history of the region is largely one of erosion of the mountains and sedimentation in the valleys. Both of these processes have been interrupted, and the Pleistocene comprised two cycles of erosion and sedimentation and part of a third, which was continued into Recent time.

⁸² Ross, C. P., *op. cit.*

The following table summarizes the events as recorded in the Gila Valley:

Events in geologic history of Gila Valley.

Period.	Epoch.	Deposition.	Erosion.
Quaternary.	Recent.	10. Silting of channels, continuing at present.	Erosion of channels, which continued until 30 years ago.
		9.	
		8. Deposition of the flood-plain materials.	
	Pleistocene.	7.	Erosion of the inner trench of Gila River.
		6. Deposition of younger alluvium (of Chemehuevis age?) to levels 75 feet above present Gila River. Outpourings of basalt.	
		5.	Minor dislocations and upheavals. Erosion of Gila River below present grade.
		4. Deposition of the older alluvium (of Temple Bar age?) to depths of 1,000 to 1,500 feet.	
(?)	(?)		
Tertiary.	Pliocene (?).	3.	Uplift and block-faulting of mountains. Followed by erosion of the mountains and beginning of the present pediments.
	Miocene (?).	2. Period of volcanism, great extensions of lava; stream-laid conglomerates; those at the base representing later part of period 1.	
	Eocene (?).	1.	General erosion of the region resulting in extensive coalescing pediments, surmounted by small mountains, and the deposition of alluvium in the valleys.

As the several parts of the Papago country present anomalous features, correlation of the events of post-Miocene time is somewhat hazardous. In addition to earth movements the known fluctuations of climate must have had their effect on erosion and sedimentation. In the table given below the history of the Gila Valley, already summarized, is compared with that of the Santa Cruz, Altar, and interior valleys of the Papago region and with that of Colorado River.

If the fluctuations of erosion and sedimentation are to be explained wholly by earth movements, then these movements must have been very complex. At the same time they must have been singularly harmonious; otherwise the Santa Cruz and Altar valleys would not have experienced conditions so similar in three separate sections of their courses. On the other hand, if changes in climate cause the fluctuations of erosion and sedimentation, then certain changes in climate which affected the region east of the Baboquivari Mountains did not affect the valleys west of the mountains.

Geologic history of certain localities in the Papago country, Ariz., and elsewhere in relation to known earth movements and postulated climatic changes.

Locality.	Pliocene uplift and humidity(?).	Early Pleistocene with basalt flows at the close, and aridity(?).	Minor earth movements and humidity(?).	Pleistocene with basalt flows toward the close and aridity(?).	Humidity(?).	Aridity(?).	Continued aridity; minor fluctuations, trend not known.
Gila Valley.....	Erosion; stage 3 a....	Deposition; stage 4..	Dislocation and erosion; stage 5.	Deposition and basalt flows; stage 6.	Erosion; stage 7....	Deposition of the flood plain; stages 8 and 9.	Deposition; stage 10.
Santa Cruz Valley and Nogales Wash above Calabasas.	Erosion of mountain pediments.	Slight fill of alluvium.	Erosion of first inner valley.	Deposition of gravel in inner valley.	Erosion to present levels of streams.	Deposition of flood-plain materials.	Recent trench in flood plain.
Santa Cruz Valley at Tubac.	Erosion of great valley and pediments near mountains.	Deposition of alluvium.	Erosion of alluvium.	Deposition of alluvium of terrace.	Erosion of alluvium.	do.....	Recent trench.
Santa Cruz Valley at Tucson.	Erosion of great valley.	Deposition of alluvium.	(?); probably faulting and erosion.	Deposition of alluvium.	Erosion of inner valley.	do.....	Do.
Santa Cruz Valley near Toltec.	do.....	Deposition.	(?).	Deposition.	(?).	Deposition.....	Deposition.
Altar Valley near head.	Erosion of pediments	(?); slight deposition in places near Altar vaca.	Erosion of inner valley.	Deposition of terrace on a few streams only.	Erosion.....	Deposition of flood plain on certain streams as Arivaca Creek.	Recent trench of Altar vaca Creek.
Altar Valley near Palo Alto.	Erosion of great valley and pediments near mountains.	Deposition.....	(?).	Deposition.....	do.....	Deposition of flood plain.	Recent trench.
Altar Valley near Robles ranch.	do.....	do.....	(?).	do.....	Erosion of pediments only.	Deposition in center of valley; erosion of pediments.	Deposition in center of valley; erosion of pediments.
Typical valley west of Baboquivari Mountains.	Erosion of pediments with deposition in center of valley.	Slight deposition on mountain pediments.	(?).	Slight deposition on mountain pediments(?).	Erosion of pediments. Continued deposition in center of valley.	Deposition in center of valley and near mountains in some localities; erosion of pediments.	Deposition in center of valley; erosion of pediments.
Colorado River b.....	Erosion of Grand Canyon and flow of Colorado in delta of Sacramento Valley.	Aggregation and volcanic activity; Temple Butte of glomerate 2,000 feet.	Rejuvenation of streams. Colorado River cuts 2,000 feet or more west of Black Mountains.	Deposition of Chemehue's gravel.	Rejuvenation of streams. Colorado River excavated old valley and cuts several short rock gorges.	Formation of flood plains.	Deposition in center of valley; erosion of pediments.

^a Lee, W. T., U. S. Geol. Survey Bull. 352 p. 67, 1908.

^b Numbers refer to table on p. 84.

GLOSSARY.⁸³

- Adobe flat.** A generally narrow plain, having a slope of 5 to 20 feet to the mile, built of fine sandy clay or adobe brought down by an ephemeral stream, having a smooth surface that is usually unmarked by stream channels, but where so marked the channels are insignificant.
- Alluvial fan.** A sloping, fan-shaped mass of loose rock material deposited by a stream at the place where it emerges from an upland into a broad valley or a plain. The highest point is at the apex of the fan, which is generally composed of boulders and cobbles that are dropped as soon as the stream emerges from its confining canyon walls. The slope of the surface near the apex may be as much as 300 feet to the mile, but it decreases toward the outer limit to as little as 10 feet to the mile. The smoothness and regularity of the surface is due to the fact that the stream soon blocks its own course with the material which it drops and so is forced to shift its channel from place to place, occupying, in time, all parts of the fan and building it up and extending it in a regular manner. If the mass of material has steep slopes it is generally called an alluvial cone, but if the slopes are relatively flat it is called an alluvial fan.
- Alluvial plain.** A plain resulting from the deposition of alluvium by water. In the southwestern United States most alluvial plains are formed by streams having a considerable grade, and hence they are generally referred to as alluvial slopes.
- Alluvial slope.** A surface composed of alluvium which slopes down and away from the sides of mountains and which merges with the plain or broad valley floor upon which it rests. The slope near the mountains may be as much as 300 feet to the mile. The plain is built by deposition from streams, commonly ephemeral or intermittent, through the union or coalescence of their alluvial fans, and is often called a fan apron, *débris* apron, or piedmont plain or slope.
- Alluvium.** The material deposited permanently or in transit by streams, including gravel, sand, silt, and clay and their mixtures and variations. Unless otherwise stated, alluvium is unconsolidated.
- Arkose.** A sand or sandstone composed of mineral fragments derived from decayed granite. A large part of the component grains are quartz and feldspar. Arkosic conglomerate is a conglomerate in which the finer material or matrix containing the boulders or pebbles is an arkose.
- Arroyo.** The channel of an ephemeral or intermittent stream, usually with vertical banks of unconsolidated material 2 feet or more high. The term is frequently applied to the stream which occupies such a channel.
- Axial stream.** The main stream of an intermontane valley, which flows along the lowest part of the valley and parallel to its longer dimension, in contradistinction to the numerous streams which flow from the mountains on either side and build up the alluvial slopes. The term is also applied to a stream which follows the axis of an anticlinal or synclinal fold.
- Barranca.** A deep break or hole made by heavy rain; a ravine; a precipice; also used in some parts of Spanish America as the equivalent of canyon; as used in New Mexico it is practically equivalent to cliff.

⁸³ This glossary of terms is prepared for the use of the lay reader and is not intended for geologists or physiographers. The scientific reader will realize that full and accurate explanations of most scientific terms in familiar language is impossible, and only a rough approximation to the full meaning can usually be given.

Base-level. The theoretical limit toward which erosion constantly tends to reduce the land. Sea level is the general base-level, but in the reduction of the land there may be many temporary base-levels below which, for the time being, the streams can not reduce the land. These temporary base-levels may be controlled by the level of a lake or a river into which the streams flow, or by a particularly resistant stratum of rock that the streams have difficulty in removing.

Boulder. A more or less rounded block of rock, commonly larger than a cobblestone. Usually boulders are rounded by being carried or rolled along by water or ice, but certain boulders have been rounded by weathering in place and are known as boulders of weathering, disintegration, or exfoliation.

Canyon. A steep-walled valley or gorge in a plateau or mountainous area. The high and precipitous slopes impress the observer more than the flat land which may occur along the stream, and on this impression depends the distinction between canyons and other valleys.

Charco. A watering place in an alluvial plain in the desert. It consists of a pool of water supplied by floods, or the basin in which such a pool is held.

Ciénaga. A swamp or swampy place. A Spanish word, in common use in the Southwest.

Corrasion. Corrasion is a term first used by Powell to designate the erosion effected by running water. Running water erodes its bed chiefly by the mechanical wear or abrasion of the rock waste which it carries against the bottom and sides of its bed, by removal of joint blocks, and by solution. Hence corrasion must be defined as consisting of these various processes.

Corrosion. Corrosion literally means gnawing away, but in this country it is generally restricted to the gnawing effected by chemical agencies—in other words, it means the solution of rocks and other material, especially in contradistinction to corrasion.

Cove. A small bay or open harbor; it is also popularly applied to small areas of plain or valley that extend into mountains or plateaus. In New Mexico and Arizona the reentrants in the borders of mesas and plateaus are also called *rincóns* (from the Spanish *rincón*, an inner corner).

Creep (of soil or rock waste). The slow movement of soil and rock waste down the slope from which these materials have been derived by weathering. Creep is due primarily to gravity but is facilitated by the presence of water, alternate wetting and drying, freezing and thawing, growth and decay of roots, and the work of burrowing animals.

Débris (rock). The material resulting from the decay and disintegration of rocks. It may occur in the place where it was produced, or it may be transported by streams of water or ice and deposited in other localities. Same as rock waste.

Decay (of rock). General disaggregation of rocks; it includes the effects of both chemical and mechanical agents of weathering, with, however, a stress on the chemical effects.

Desert varnish. A surface stain or crust of manganese or iron oxide, of brown or black color and usually with a glistening luster, which characterizes many exposed rock surfaces in the desert. It coats not only ledges of rock in place but also boulders and pebbles that are scattered over the surface of the ground.

Dip slope. A slope of the land surface which conforms approximately to the dip of the underlying rocks.

Disintegration. The process by which through the differential expansion of the minerals in a rock due to changes in temperature or through the partial solution or change due to the absorption of water the rock is disrupted into its component mineral fragments.

Dissected. Cut by erosion into hills and valleys or into flat interstream areas and valleys, as dissected plateau or pediment.

Dissection. The work of erosion in destroying the continuity of a relatively even surface by the cutting of ravines or valleys.

Ephemeral stream. A stream or portion of a stream which flows only in direct response to precipitation. It receives little or no water from springs and no long-continued supply from melting snow or other sources. Its channel is at all times above the water table. The term may be arbitrarily restricted to streams or portions of streams which do not flow continuously during periods of one month.

Erosion. A term which includes all processes by which earthy matter or rock is loosened and removed from place to place. In this country it is regarded as including weathering, corrosion, and transportation.

Exfoliation. The process by which under changes of temperature or other causes successive sheets of rock are split off the parent mass.

Fanglomerate. A fanglomerate is composed of heterogeneous materials which were originally deposited in an alluvial fan but which since deposition have been cemented into solid rock.

Flood plain. A strip of relatively smooth land bordering a stream, built of sediment carried by the stream and dropped in the slack water beyond the influence of the swiftest current. It is called a living flood plain if it is overflowed in times of high water, but a fossil flood plain if it is beyond the reach of the highest flood.

Insolation. Exposure to the sun's rays, and hence the effect of the sun's rays on the materials composing the surface of the earth. This is usually spoken of as the effect of changes of temperature and consists of exfoliation and the breaking up of rock and rock fragments.

Land form. The term land form is applied by physiographers to each one of the multitudinous features that taken together make up the surface of the earth. It includes all broad features, such as plain, plateau, and mountain, and also all the minor features, such as hill, valley, slope, canyon, arroyo, and alluvial fan. Most of these features are the products of erosion, but the term includes also all forms due to sedimentation and to movements within the crust of the earth.

Lateral planation. The reduction of the land in interstream areas to a plane parallel to the stream profile, effected by the lateral swinging of the stream against its banks.

Mesa. A Spanish word meaning table. Strictly applicable to those level or nearly level masses of land of relatively small extent which stand distinctly above the surrounding country, as a table stands above the floor upon which it rests. It is loosely applied, however, to any broad, flat surface of moderate elevation which is bounded on at least one side by a cliff or steep slope.

Mountain pediment. A plain which lies at the foot of mountains in an arid region or in headwater basins within a mountain mass. The name is applied because the plain appears to be a pediment upon which the mountain stands. A mountain pediment is formed by the erosion and deposition of streams, usually of the ephemeral type, and is covered with a veneer of gravel in transit from higher to lower levels. It simulates the form of an alluvial slope.

Mountain slope. The sloping surface which forms the side of a mountain; specifically the slope characteristically developed by the processes of erosion in an arid region.

Niche. A cave or reentrant in a rock face or beneath a waterfall.

Peñasco. A Spanish word meaning a large rock. It is commonly used in the Southwest for a projecting rock, such as those isolated by the recession of cliffs or mountain slopes. "Pillar" (pillar) has the same significance.

Picacho. A peak or sharply pointed hill or mountain. Because of the steep slopes of mountains in the desert region, picacho appears as the name of numerous mountains in southwestern Arizona.

Plateau. A table-land or flat-topped region of considerable elevation and extent. A plateau is commonly higher than a mesa and usually more extensive. It may have an undulating surface and from it may rise mountains, or it may be dissected by the cutting of canyons. If a large part of the original surface has been destroyed by streams, it is called a dissected plateau.

Playa. A Spanish word meaning literally shore or strand; a level or nearly level area that occupies the lowest part of a completely closed basin and that is covered with water at irregular intervals and for longer or shorter periods of time, forming a temporary lake. It is generally composed of evenly stratified beds of clay or silt that have been deposited in a temporary lake and that may contain large amounts of soluble salts. The surface is usually devoid of vegetation and may be either hard or soft and smooth or rough. Playas are frequently called "dry lakes," and other terms, such as "alkali flats" or "salinas," are used either in a general sense or to designate playas of special types.

Rain wash. The water from rain, after it has fallen on the surface of the ground and before it has been concentrated into definite streams; the work done by this water in striking the earth's surface and in transporting débris.

Recession of slopes. The moving back or receding of slopes from a former position without change in the angle of slope; comparable to cliff recession.

Regimen of a stream. The system or order characteristic of a stream—in other words, its habits with respect to velocity and volume, form of and changes in channel, capacity to transport sediment, amount of material supplied for transportation, etc. The term is also applied to a stream which has reached an equilibrium between corrasion and deposition or, in other words, to a graded stream. — *very rare*

Rincon. See Cove.

Rock shelter. A shallow cave or reentrant under an overhanging cliff.

Rock waste. Same as rock débris. See Débris.

Rubble. Rough, irregular pieces of broken rock.

Sediment. In the singular the word is usually applied to material in suspension in water or recently deposited from suspension. In the plural the word is applied to all kinds of deposits from the waters of streams, lakes, or seas, and in a more general sense to deposits of wind and ice. Such deposits that have been consolidated are generally referred to as sedimentary rocks.

Sedimentation. The act or processes of deposition of materials from suspension in the water of streams, lakes, and seas. Sometimes extended to cover deposition by wind and ice.

Sheet flood. A flood which spreads as a thin sheet of water over a large area and is not concentrated in channels. Sheet floods are of short duration, generally being measured in minutes or hours, and the water is always muddy. They are characteristic of the alluvial areas of the Papago country.

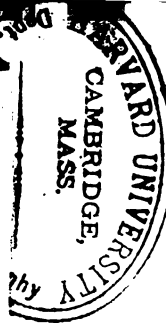
Sierra. A Spanish word meaning saw; applied to mountains. The typical sierra is longer than it is broad and presents to the observer, when viewed from the side, a jagged crest, which decreases in altitude from a point near the middle toward each end. Its slopes are scored by narrow gorges or canyons, between which are projecting ridges.

Talus. The sloping heap of loose rock fragments lying at the foot of a cliff or steep slope.

Terrace. A plain, natural or artificial, from which the surface descends on one side and ascends on the other. Terraces are commonly long and narrow, and they border seas, lakes, or interior valleys. A terrace may be built up by the deposition of sediment from water, it may be cut by the breaking of waves on a shore or the sweeping of currents, or it may be formed by the dislocation of the rocks in crustal movements. The descent from river terraces toward the river may be very abrupt, especially in arid regions; the ascent on the other side may be only that of an extensive alluvial slope.

Weathering. The effect of atmospheric agents on rocks and the processes by which rocks are affected by these agents.





Sheet flo
and 1
gener
mudd
count

Sierra.
sierra
from
near
or ca

Talus. 2
steep

Terrace.
side
and
up b
of w
the c
terra
the s

Weather
whic



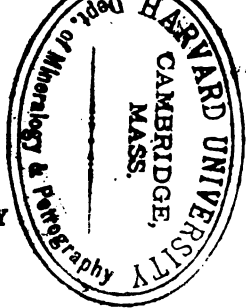
DEPARTMENT OF THE INTERIOR

ALBERT B. FALL, Secretary

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, Director

Bulletin 730—C



THE SHAPES OF PEBBLES

PAPERS BY

CHESTER K. WENTWORTH

Contributions to the geography of the United States, 1922

(Pages 91-114)

Published June 26, 1922



WASHINGTON

GOVERNMENT PRINTING OFFICE

1922

CONTENTS.

	Page.
A method of measuring and plotting the shapes of pebbles.....	91
Introduction.....	91
The problem.....	91
Method and results.....	93
Measurements of curvature.....	93
Results.....	97
A field study of the shapes of river pebbles.....	103
Introduction.....	103
The field.....	105
Method of work.....	106
Significance of results.....	109

ILLUSTRATIONS.

	Page.
PLATE XIV. <i>A</i> , Convexity gage; <i>B</i> , Glacial and sand-blasted pebbles before artificial abrasion; <i>C</i> , Glacial and sand-blasted pebbles modified by artificial abrasion.....	94
XV. <i>A</i> , Striated glacial pebbles from Afton Junction, Iowa; <i>B</i> , Glacial pebbles from Afton Junction, Iowa; <i>C</i> , Tumbling barrel in which experimental studies of abrasion of pebbles are made....	95
FIGURE 26. Profiles and table showing shapes of pebbles.....	94
27. Convexity gage.....	94
28. Modified convexity gage.....	95
29. Profile from which block <i>dd</i> in figure 28 was constructed.....	95
30. Circular logarithmic scale.....	96
31. Stylus for use with nomographic chart.....	96
32. Chart showing characteristic positions of different types of pebbles.....	98
33. Axial line of migration in shape of a river pebble.....	99
34. Graph showing modification in shape of five glacial pebbles that were subjected to abrasion in a tumbling mill.....	100
35. Graph showing modification in shape of five sand-blasted pebbles that were subjected to abrasion in a tumbling mill.....	101
36. Sketch map of vicinity of Russell Fork of Big Sandy River, Va..	104
37. Profile of the upper course of Russell Fork of Big Sandy River, Va.	105
38. Chart showing distribution according to shape of 642 river pebbles, cobbles, and boulders from Russell Fork of Big Sandy River, Va.	107
39. Curves showing relation of roundness of pebbles to distance of transportation.....	108
40. Curves showing relation of roundness ratios to size of pebbles....	109
41. Final curve of rounding of pebbles with respect to distance traveled.	110
42. Comparison of curves of rounding of pebbles with respect to distance traveled, obtained by field and experimental measurements....	111

A METHOD OF MEASURING AND PLOTTING THE SHAPES OF PEBBLES.

By CHESTER K. WENTWORTH.

INTRODUCTION.

The studies of which this paper is a report of progress were begun by the writer at the University of Chicago in 1917 and have since been carried on under the auspices of the United States Geological Survey, both in the field and in the office. Since October, 1920, the work has been done in the department of geology of the State University of Iowa, with the continued cooperation of the Federal Survey. The writer is indebted for suggestions and assistance to numerous friends at all these places. He would be grateful for comment and criticism and particularly for suggestions of localities for studying special conditions and products of pebble-shaping processes.

In a brief but suggestive paper H. E. Gregory¹ says, "Attempts to establish criteria for distinguishing beach pebbles from those formed by rivers, glaciers, or wind or resulting from weathering in place have led to unsatisfactory results." He goes on to show that most of the specific characteristics ascribed to pebbles of different origin are produced only by special sets of conditions and that most of the generalizations which have been made are either untrue or so vague as to be unreliable for the discrimination of deposits in the field. It is true that in a broad way it is possible to distinguish on sight between river pebbles, glacial pebbles, and sand-blasted pebbles. On the other hand, the general separation of beach pebbles from river pebbles can not be made with certainty on the basis of any criteria yet set forth.

THE PROBLEM.

In describing the method of measurement which is outlined below the writer makes no pretense of offering a complete solution of this problem. He desires rather to present the procedure which has been found useful in denoting numerically some of the most significant features of the shapes of pebbles, with the confidence that final success in distinguishing the genetic groups of pebbles by their shapes lies in the use of quantitative methods. The shapes of pebbles might be classified in numerous ways, but the classification most

¹ Gregory, H. E., Note on the shape of pebbles: *Am. Jour. Sci.*, 4th ser., vol. 39, pp. 300-304, 1915.

likely to be of use to the geologist is genetic. The first factor to be considered is the structure of the parent rock; the second is the agent by which the shape of the pebble is modified; the third is the time factor or stage of the process of modification.

The structure of the original rock finds expression in two principal ways—in its effect on the shapes of fragments produced by the agents of weathering and in its effect on shapes developed from these detrital fragments by the agent or agents of transportation. Although much is known in a broad way concerning the results of weathering and some general qualitative observations have been made on the shapes of the fragments produced, no careful study of the shapes of the products of the different processes of mechanical weathering has yet been made.

Without an attempt to outline here the manifold processes and products of weathering that result in clastic fragments the following may be mentioned:

Exfoliation.	Plucking.
Splitting.	Wedge work of ice.
Crumbling.	Nivation.
Sun flaking.	Moisture changes.
Jointing.	Hydrostatic wedge work of waves.
Wedge work of plant roots.	Wedge work of pebbles in cracks.

Others will occur to one who attempts to make even an "armchair" analysis of the whole process of weathering. Each of these agents has its peculiar effect in the shapes of the pieces produced. Fragments produced by exfoliation differ in shape from those produced by crumbling as a result of differential thermal expansion in different minerals, and both differ in shape from fragments produced by jointing. It is highly probable also that the shapes of fragments due to the single process of exfoliation differ with each of numerous factors, such as amount and rapidity of diurnal change in temperature and the conductivity, specific heat, thermal-expansion coefficient, and elasticity of the rock.

The shapes of disrupted fragments from a given rock in a given region are due in general to a combination of several of the agents suggested above rather than to any one alone. Each agent finds a different expression in rocks of different types; as, for example, coarse or fine grained igneous rock, schist, gneiss, and bedded sedimentary rocks of divers kinds. Evidently the problem of the shapes of the fragments that result from rock disruption is complicated. It is worthy of study, however, for the original shapes of fragments that are carried and abraded by the various transporting agents are relatively persistent for great distances and have considerable influence on the forms assumed by these fragments in stages of their history. Quantitative work in great detail on this question of original

shapes is needed to furnish an adequate basis for studies of the generic shape characteristics of pebbles.

It is evident from the foregoing statements that there are an infinite number of shapes of fragments available for transportation. These shapes are believed to belong to a large number of types, which present knowledge does not suffice to describe in detail. They include flat slabs and tabloid forms of quadrangular or irregular profile, joint-bounded blocks, shell-like "exfoliates," fantastic nodular pieces of limestone, and many other types. In his attempt to evaluate the modifications of shape which result in the formation of pebbles, the writer has been obliged to seek as a starting point some one characteristic that is common to all or nearly all the types. That characteristic is angularity, and it is valuable also in the fact that it is the characteristic most quickly and most persistently modified in transportation. There are probably original shapes which are not angular, but it seems unlikely that any other simple characteristic is so generally present as that of angularity, which is, therefore, the basis of the writer's study.

METHOD AND RESULTS.

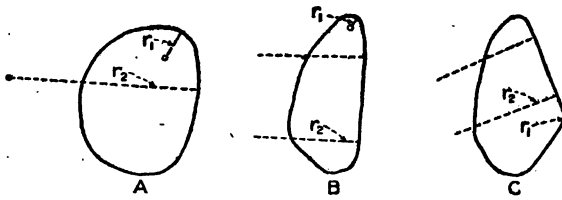
Theoretically, it is possible to measure any number of specific features of shape, but a practical limit is set by the need of reasonable dispatch and of the use of simple instruments. Because of the desirability of using a coordinate system of plotting in two dimensions only two characteristics have been used in the present scheme. One, which may be called the roundness ratio, is $\frac{r_1}{R}$, in which r_1 is the radius of curvature of the sharpest developed² edge and R is the mean radius of the pebble. The other, the flatness ratio, is $\frac{r_2}{R}$, in which r_2 is the radius of curvature in the most convex direction on the flattest developed face or portion of the surface, and R is the same as before.

MEASUREMENTS OF CURVATURE.

An inspection of figure 26 will make clear the relation of the values of r_1 and r_2 to the shape of the pebble as shown in profile. These radii are measured by a simple contact method, with an instrument similar to the gage used by opticians to measure the curvature of lenses. A brief description of the gage is here presented in the hope that it may be helpful to others who may need to make the same or similar measurements or to whom it may suggest other instrumental adaptations.

² By the use of the term "developed" an attempt is made to discriminate between edges and facets due mainly to abrasive modification, which may be called developed, and those present on the original fractured piece and not due to the work of the transporting agent. The writer is well aware that this line must be drawn arbitrarily according to the judgment of each observer, but he has not yet been able to devise a method of eliminating this undesirable personal factor.

The gage shown in Plate XIV, A, and figure 27 was adapted from a test indicator manufactured by the L. S. Starrett Co. The instru-



	r_1	r_2	R	$\frac{r_1}{R}$	$\frac{r_2}{R}$
A	8mm.	50mm.	18mm.	.44	2.7
B	3mm.	500mm.	15mm.	.20	33.3
C	2mm.	250mm.	17mm.	.012	14.7

FIGURE 26.—Profiles and table showing shapes of pebbles and corresponding values of r_1 and r_2 and the ratios derived from these values.

ment, as constructed originally, was designed to indicate motion of its test point by gradations of 0.001 inch, each turn of the pointer corresponding to 0.1 inch, and the total motion possible was slightly over 0.2 inch. This gage was first adapted to the measurement of

convexity by the attachment of two fixed points e, e, as shown in figure 27.

If A equals the distance between the fixed points in inches and B equals the amount of motion of the movable point above the plane of the fixed points expressed in inches, then r, the radius of curvature in millimeters of the surface brought into contact with the instrument, may be computed by the following formula:

$$r = 25.4 \frac{A^2 + 4B^2}{8B}$$

or

$$r = 3.175 \left(\frac{A^2}{B} + 4B \right)$$

This arrangement results in very high relative accuracy of reading for the value of r when r is small, but very low relative accuracy of reading when r is large, as is shown by the following table, giving equivalent values of r and B for A at a constant value of 0.1 inch.

r (milli-meters).	B (Inch).
2	0.018
3	.011
200	.000170
300	.000106

The difference in readings or values of B between 2 and 3 millimeters radius is thus 0.007 inch, an amount readily readable, whereas

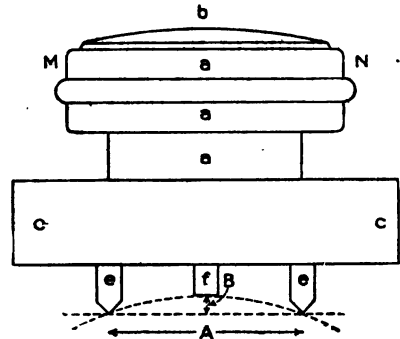
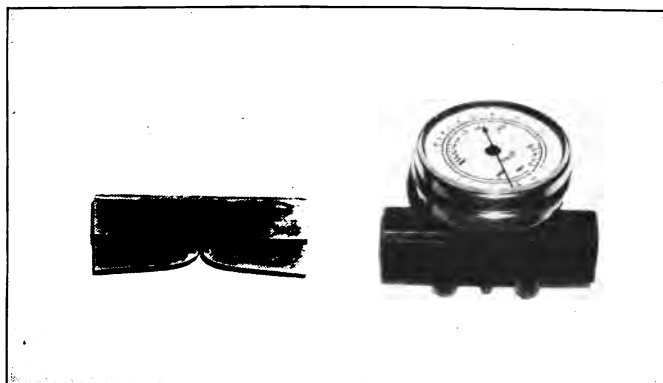


FIGURE 27.—Convexity gage. a, a, a, Original gage; b, edge of the crystal over the dial; f, movable point; c, c, block for the attachment of the points e, e.



A. CONVEXITY GAGE.



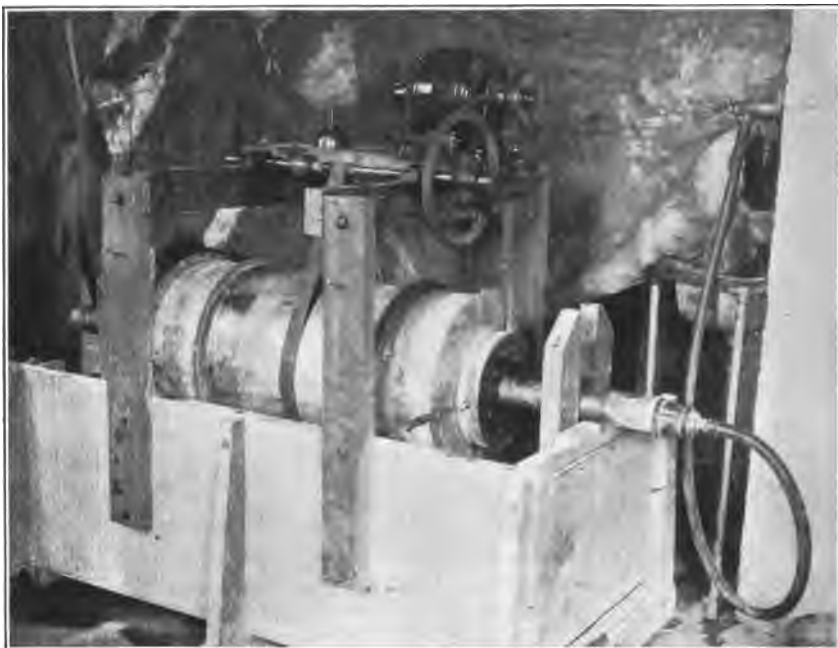
B. GLACIAL AND SAND-BLASTED
PEBBLES BEFORE ARTIFICIAL
ABRASION.

C. GLACIAL AND SAND-BLASTED
PEBBLES MODIFIED BY ARTIFICIAL
ABRASION.



A. STRIATED GLACIAL PEBBLES FROM
AFTON JUNCTION, IOWA.

B. GLACIAL PEBBLES FROM AFTON
JUNCTION, IOWA.



C. TUMBLING BARREL IN WHICH EXPERIMENTAL STUDIES OF ABRASION
OF PEBBLES ARE MADE.

that between 200 and 300 millimeters radius, which represents an equal relative change in r , is only 0.000064 inch, an amount quite too small to be read on the dial. If the value of A is increased, the range in reading is greatly reduced.

Figure 28 shows the device which was used to obviate the difficulty. The profile of the block dd was designed as shown in figure 29. a, b, c, d, e , and f are circles whose centers lie on the line AB , produced if necessary. Their nearest points to A are equally spaced, so that $ab = bc = cd$, etc. Their radii are in geometric series, so that

$$\frac{r_a}{r_b} = \frac{r_b}{r_c} = \frac{r_c}{r_d}, \text{ etc. By drawing a}$$

series of such circles on a greatly enlarged scale and then drawing the enveloping curves CD and EF , a profile was obtained which was then reduced photographically to true scale and used in forming the profile block shown in figure 28. The valuable property of this profile is that equal relative changes or equal ratios between the radii of successive

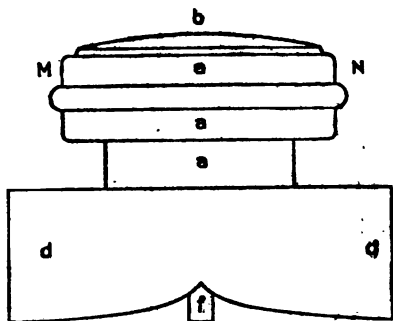


FIGURE 28.—Modified convexity gage. d, d , Profile block.

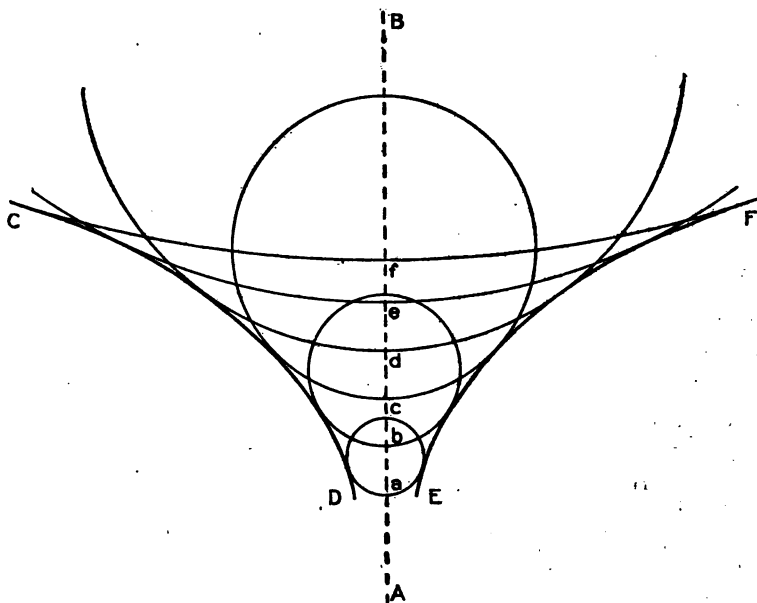


FIGURE 29.—Profile from which block d, d in figure 28 was constructed.

circular curves applied to the profile produce equal changes in the angular displacements of the recording pointer. Thus the instrument may be read everywhere within its range with the same relative accuracy. As constructed with a motion of about 0.170 inch of the pointer, radii of curvature from 1 to 3,000 millimeters are indicated,

and 1 per cent variation of radius is equivalent to a motion of about 0.2 millimeter on the circular scale. The circular scale reading in 0.001 inch was replaced by a circular scale which was devised to read direct to mil-

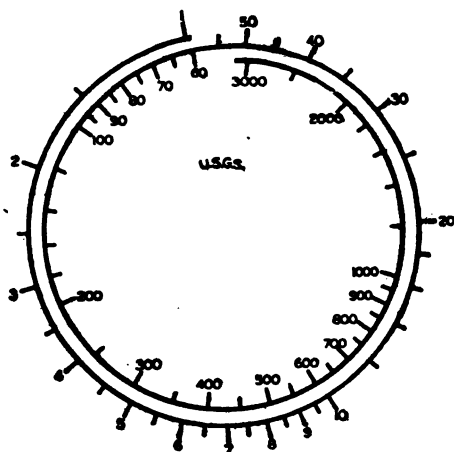


FIGURE 30.—Circular logarithmic scale.

limeters of radius and which, because of the form of the profile, is a circular logarithmic scale. It is shown in figure 30. This new scale was then placed in position in the plane MN (fig. 28.)

The instrument thus equipped has been found admirable as a compact and portable device for the measurement of nearly circular curves, with a moderate accuracy through a 3,000-fold range of radii of curvature. R is most conveniently computed³ as the half mean of length, breadth,

and thickness as measured in the field, or, more quickly and better still, computed from the weight and density as measured in the laboratory.

³ Strictly the mean radius R for a triaxial ellipsoid is one-half the geometric mean of the length, breadth, and thickness—that is,

$$R = \frac{1}{2} \sqrt{D' D'' D'''} \dots \dots \dots (1)$$

but for the purposes of this paper the arithmetic mean, or

$$R = \frac{D' + D'' + D'''}{6} \dots \dots \dots (2)$$

is quite accurate enough. However, if the computing is done graphically by the use of alinement or nomographic charts, the first and more correct computation (equation 1) may be made with equal facility and speed by the use of logarithms instead of arithmetic scales. Problems of the form of equation 1 have been solved by the writer to an accuracy of two significant figures, at the rate of more than four a minute by the use of such charts.

In the use of nomographic or alinement charts for rapid computation where only moderate accuracy is required, the writer has found a black thread more satisfactory than a straight edge or a celluloid sheet with black line on the under side. The thread, though slightly thicker and therefore of slightly less ultimate accuracy, may be handled much more rapidly and conveniently. If, however, the thread is held in the fingers at both ends, there is the difficulty that each end setting is disturbed while the other end is being set and it is necessary to glance to and fro several times before a final reading is made.

This difficulty was eliminated by the construction of a stylus having one end tapered nearly to a point and having a small hole at the end of the taper (fig. 31). A thread may be inserted in the hole and, by means of the cross hole, secured by tying a knot. By holding the stylus in one hand, one end of the thread may be placed exactly on the scale as desired and with the other hand the other end of the thread may be set without disturbing the initial setting, as the straightened thread pivots about the exact initial point on the scale. The stylus is made hollow for lightness, being constructed of brass tube with the two end pieces soldered into it. The writer has found that much higher speed and greater accuracy can be attained by the use of this device. Similar instruments have doubtless been constructed by others but have not, so far as known, been previously described.

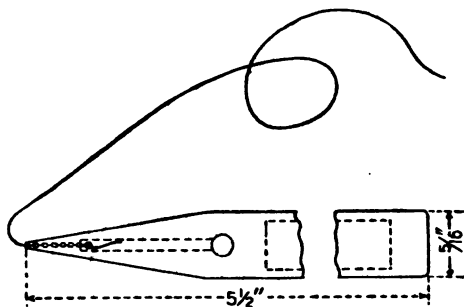


FIGURE 31.—Stylus for use with nomographic chart.

RESULTS.

Figure 26 gives in tabular form the measured and computed results on three pebbles of different shapes as seen in profile. When the values of $\frac{r_1}{R}$ and $\frac{r_2}{R}$ for each pebble have been obtained, the position of the pebble is plotted on a double logarithmic chart, the former ratio being used as ordinate and the latter as abscissa. The reasons for the choice of r_1 and R as defined are apparent when it is considered that the largest value which the radius of curvature of the sharpest edge of any piece can have is the radius of the piece, and the limiting condition is that where $r_1 = R$ —that is, the piece is a sphere, and the value of $\frac{r_1}{R} = 1$. The values of $\frac{r_1}{R}$ always lie between 0 and 1.

Figure 32 shows the approximate boundaries of three principal shapes of pebbles plotted in this fashion. It follows from the ratios used that a sphere will fall at the top of the chart one-third of the distance from the left corner. Angular pieces with no facets whatever fall outside the chart at the left and bottom. Pebbles with nearly plane facets will fall at or beyond the right edge. The boundary lines for river pebbles are determined from 642 river pebbles measured in the upper course of Russell Fork of Big Sandy River, Va., as reported in the following paper (pp. 103–114). Those for glacial pebbles and sand-blasted pebbles⁴ were determined from positions of 40 specimens of each and are probably subject to slight revision when more specimens have been measured. The large dots in each of the latter groups indicate the positions of the 10 pebbles with which the preliminary studies were made to choose the best mode of plotting the measured values. It is significant to note that of 642 pebbles chosen at random from a stream in Virginia, only 3 come within the boundary line for glacial pebbles. More measurements of glacial pebbles may produce a slight confusion along this zone of contact, but there is nevertheless a rather distinctive separation of the two groups. Even more satisfactory is the dispersal on the chart of the glacial and sand-blasted pebbles, where there seems to be little likelihood of confusion.

It should be borne in mind that great reliance can not be placed on the shape of a single pebble. Only the study of 50 or 100 pebbles will give the true shape norm of a deposit with reasonable accuracy, though a study of 10 or 15, where no more were available, might be suggestive. However, as is shown by figure 32, it seems that a wide departure of even a single pebble from the mean shape for its particular mode of origin is very rare. Figure 33 shows the axial line of migration of a river pebble from angularity to sphericity as accurately as it has been determined so far.

⁴ The writer is indebted to Dr. J. B. Woodworth for an excellent collection of sand-blasted pebbles from Marthas Vineyard, Mass., which was used in this study.

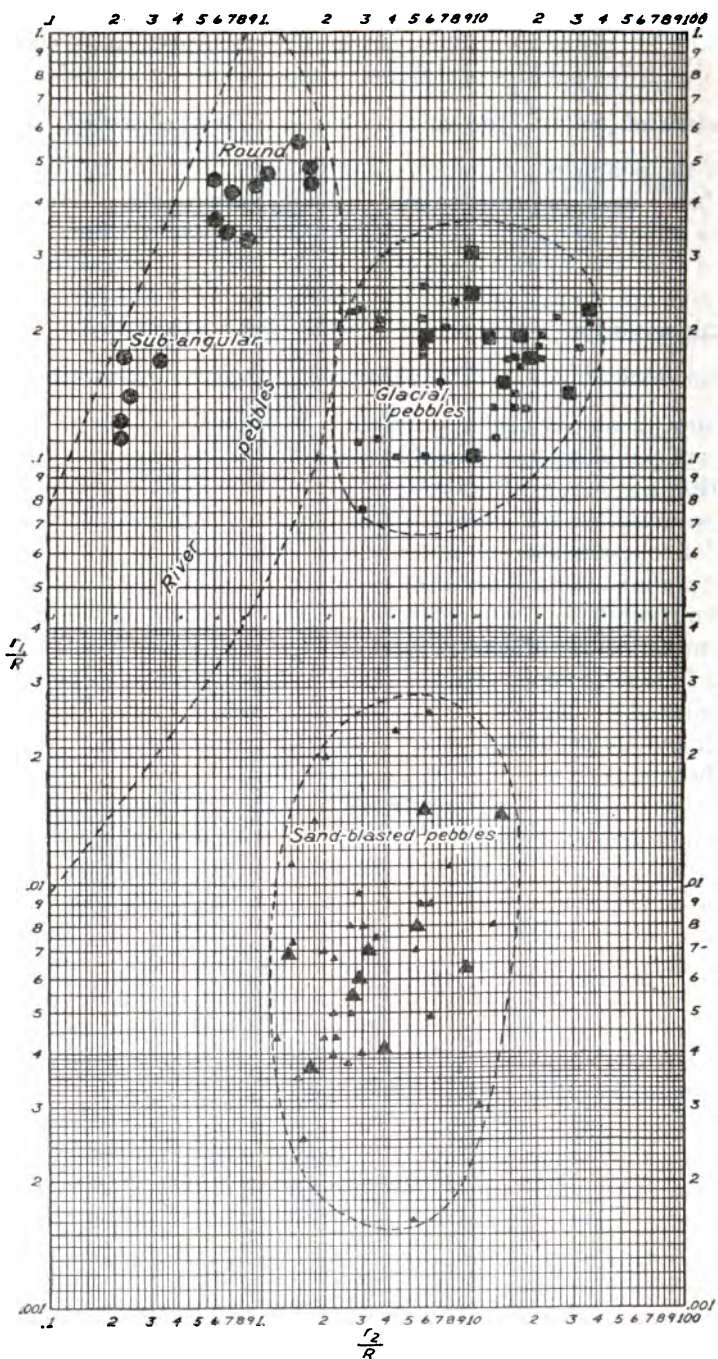


FIGURE 32.—Chart showing characteristic positions of different types of pebbles, according to the scheme of measurement used in this paper.

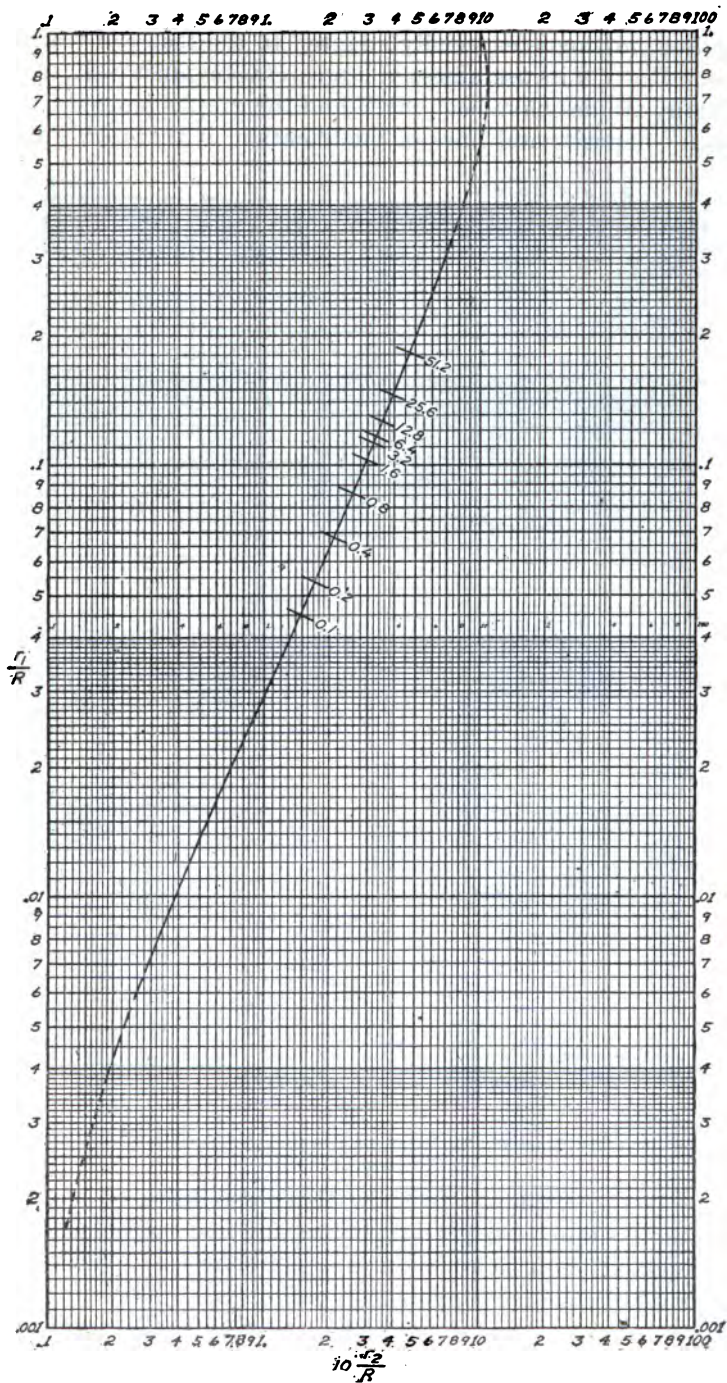


FIGURE 33.—Axial line of migration in shape of a river pebble.

In addition to the allocation of pebbles of nearly pure origin, this method of plotting is especially adapted to the study of transitional shapes. Much of its usefulness in interpretation must wait, of course, until many studies have been made and the graphs plotted of certain "normal" deposits and lines of modification, if there are such lines

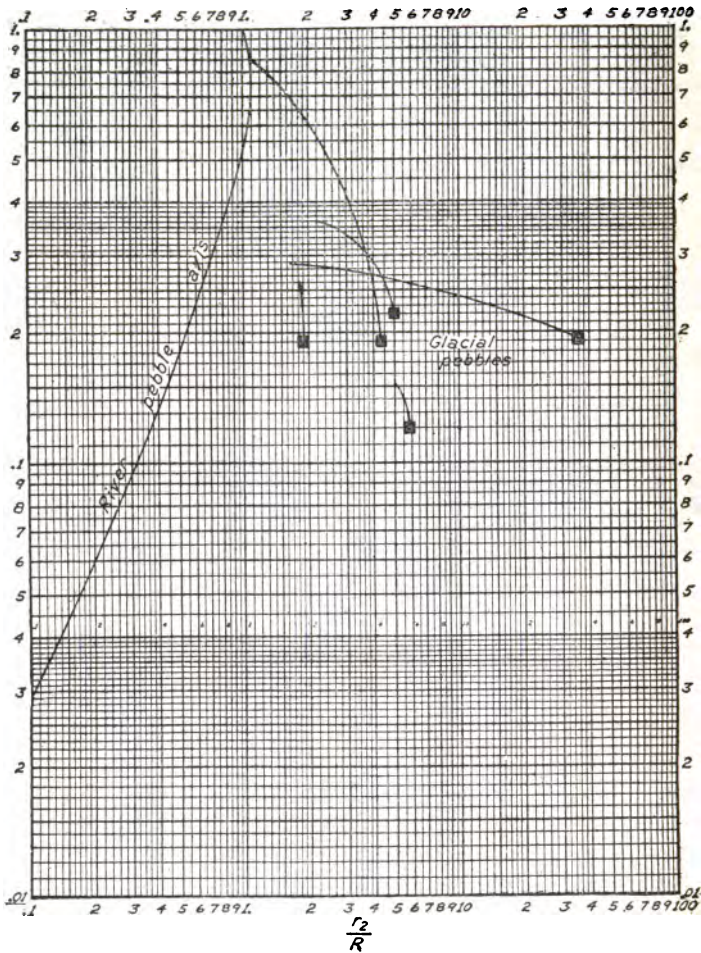


FIGURE 34.—Graph showing modification in shape of five glacial pebbles that were subjected to abrasion in a tumbling mill.

in matters so complex. To show the possibilities of such studies, the writer has taken five glacial pebbles and five sand-blasted pebbles and subjected them to abrasion in a tumbling mill. This abrasion, as is shown in the accompanying paper, is closely similar in its effect upon shapes to that produced under natural river conditions. The shapes of the pebbles were measured from time to time, and the lines of modification in shape were plotted as shown in figures 34 and 35.

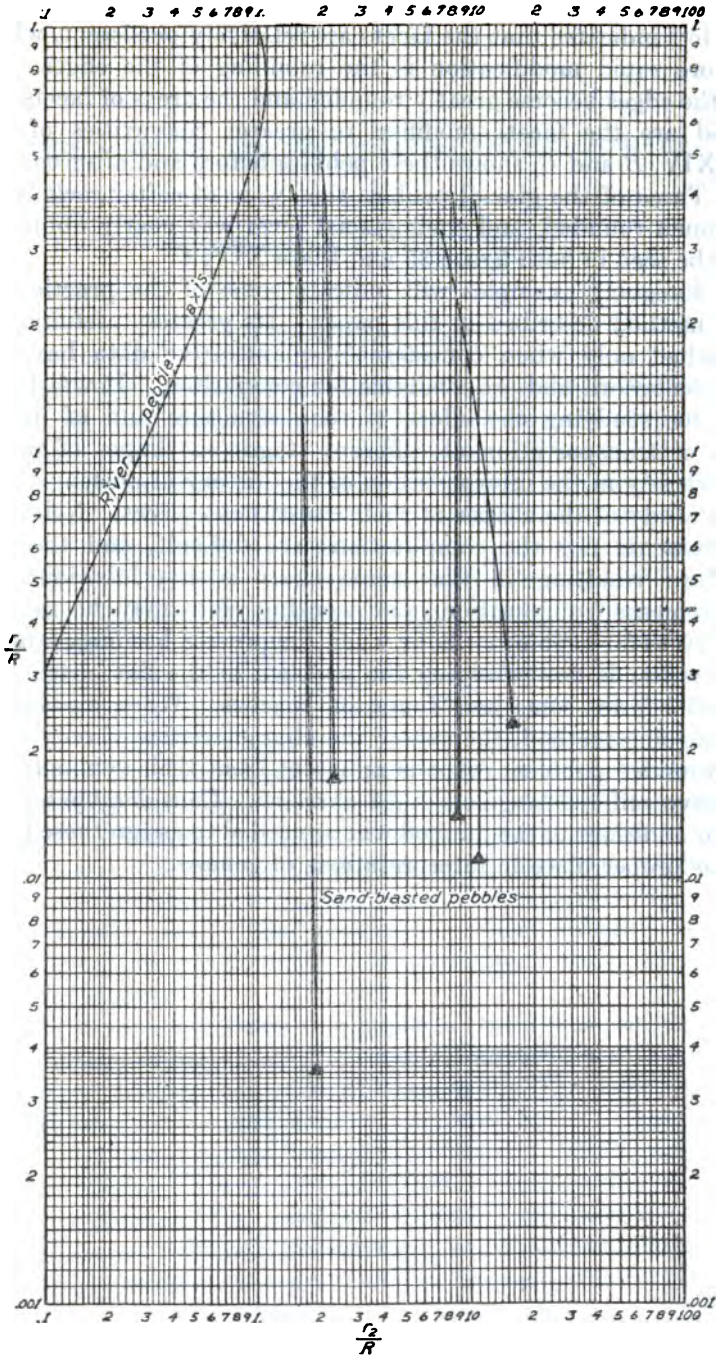


FIGURE 35.—Graph showing modification in shape of five sand-blasted pebbles that were subjected to abrasion in a tumbling mill.

The dominant vertical trend of these lines with only slight trend to the left indicates that the facets are relatively persistent, whereas the more rapid modification is the rounding of the edges. Only when the edges become greatly rounded and the areas of facets much reduced are the facets modified to greater convexities of form. Plate XIV, *B* and *C*, shows these pebbles before and after the abrasion. Three of the glacial pebbles that were of softer rock became very much rounded, and their glacial form was nearly obliterated, as will be seen in both figure 35 and Plate XIV, *C*.

The foregoing examples will indicate some of the practical uses of the method described in this paper. Its greatest usefulness will be reached only when considerable quantitative data have been placed on record and are available for comparison. It will then be useful for studying the effect of rock structure and of different agents of transportation at different stages on shapes of pebbles, and inversely in the interpretation of the history of ancient deposits from a study of the shapes of their constituent pieces. Neither the measurements nor the computations are difficult, and the whole procedure resulting in the shape chart is not laborious. The measurements, computations, and working plots may be made for about 20 to 30 pebbles an hour when the process becomes familiar.

The writer is now studying the problem of the flat, discoid, and ellipsoidal forms sometimes found on beaches. When measured by the foregoing method, they show the characteristics of only moderately rounded pebbles, yet it is apparent from their symmetry that they have suffered long-continued abrasion. Considerable modifications or additions to the method will be needed to assign these pebbles to their proper place in interpretations of genesis.

A FIELD STUDY OF THE SHAPES OF RIVER PEBBLES.

By **CHESTER K. WENTWORTH**

INTRODUCTION.

The study here reported was undertaken in order to determine the relation between the roundness of pebbles and the distance they have been transported by running water. That pebbles become less and less angular and approach rounded, spheroidal forms as they travel farther and farther downstream has long been an axiom in geology. Qualitatively, this fact is amply proved by casual field observations. To the writer's knowledge, no quantitative field study has heretofore been made of this relation between roundness and distance.

The writer has been engaged for several years in experimental measurements of pebble rounding.¹ The results of these studies, though of value for comparisons, have obviously been open to the criticism of being obtained under highly artificial conditions and hence not being applicable to field problems. The study here reported has rendered available data from a large number of measurements of river pebbles and also, through comparison of these data with the experimental data, has proved conclusively that the two sets of results are in close agreement. Much valuable work may therefore be done by the experimental method, which affords better facilities for control.

The field work on which this paper is based was done in connection with the investigation of the coal resources of southwestern Virginia under the direction of M. R. Campbell. The work was carried on under cooperative agreement between the United States Geological Survey and the Virginia Geological Survey. While studying the course of Russell Fork of Big Sandy River from another standpoint,² the writer discovered a peculiarly favorable situation for the study of the shapes of pebbles. Accordingly, in September, 1920, he spent four days in making measurements in the field, taking readings of

¹ Wentworth, C. K., A laboratory and field study of cobble abrasion: *Jour. Geology*, vol. 27, pp. 507-521, 1919.

² Wentworth, C. K., Russell Fork fault of southwest Virginia: *Jour. Geology*, vol. 29, pp. 351-369, 1921.

three diameters and an average of four convexities on each of 642 pebbles. The subsequent computations and plotting and the experimental work with the tumbling barrel were done in the geologic laboratory at the State University of Iowa. A considerable part of

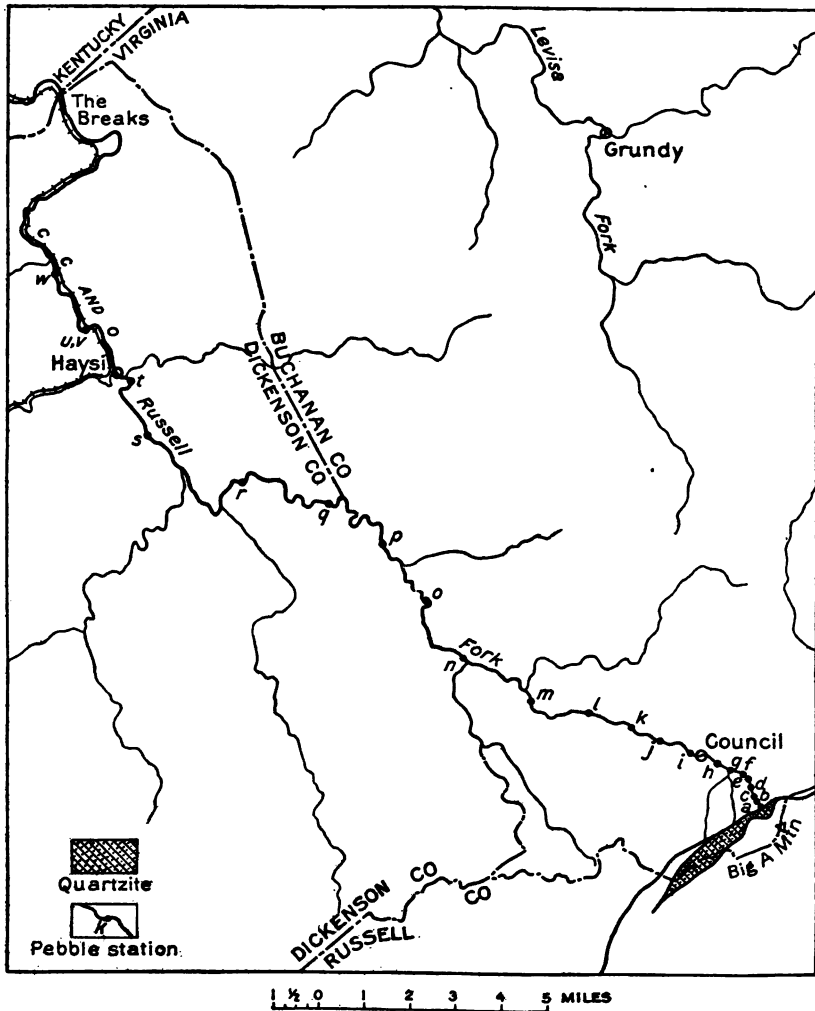


FIGURE 36.—Sketch map of vicinity of Russell Fork of Big Sandy River, Va.

the apparatus there used was furnished by the United States Geological Survey. The writer wishes to acknowledge his indebtedness to many friends for suggestions in the course of the work. Special thanks are due to Messrs. M. I. Goldman and A. C. Trowbridge for their valuable assistance and criticism.

THE FIELD.

Russell Fork of Big Sandy River, in southwestern Virginia (fig. 36), rises on the north flank of Big A Mountain, a high point on Sandy Ridge, which lies between the Clinch River drainage basin on the south and the Big Sandy River drainage basin on the north. Russell Fork flows in a general northerly direction across nearly horizontal Pennsylvanian rocks from Big A Mountain to The Breaks, where it has cut a magnificent gorge through the harder rocks of the core of the Pine Mountain anticline. Beyond Pine Mountain it joins other streams to form Big Sandy River, which is tributary to the Ohio. The head of the permanent stream of Russell Fork is at an elevation of about 2,600 feet. It falls about 1,200 feet in the first 10 miles and has a considerably lower gradient for the next 18 or 20

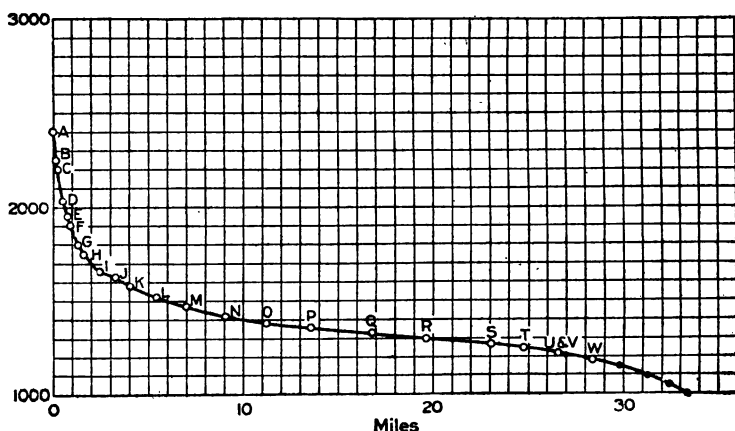


FIGURE 37.—Profile of the upper course of Russell Fork of Big Sandy River, Va.

miles (fig. 37). There is a slight break in the profile and a progressive increase of gradient starting at about 14 miles from station A. This increase of gradient continues well through The Breaks, and the gradient again becomes lower beyond the Pine Mountain barrier. Only the upper portion of the course of Russell Fork, down to station W (fig. 37), which is about 2 miles above The Breaks, is discussed in this paper.

At station A, at an elevation of 2,400 feet, there is exposed a quartzite of pre-Carboniferous age. It is not more than 100 feet thick and is exposed in this situation as a result of an overthrust from the south, the entire upper part of Big A Mountain consisting of overthrust material. The quartzite is a yellow vitreous to white sugary rock which is the source of many yellow and brown "casehardened" cobbles and pebbles that can be distinguished in the gravel bars for many miles downstream from cobbles and pebbles composed of the local Carboniferous sandstone. No rock likely to be confused

with the quartzite is exposed at any other place in the basin of Russell Fork above The Breaks. It is thus apparent that all pebbles of quartzite in the valley or channel of the stream have come from the exposure at or very near station A, and the distance which each pebble has traveled is therefore readily determinable.

METHOD OF WORK.

The method of field study consisted in measuring the length, breadth, and thickness of the pebbles, the radius of curvature of the sharpest edge, and the radius of curvature of the flattest developed face. (See preceding paper, pp. 91-102.) The linear measurements were made with a steel tape and the measurements of convexity with the gage described on page 94. The pebbles, cobbles, and boulders were collected in groups of 10 to 70 at stations designated by letters on the map and profile (figs. 36, 37). In the upper part of the valley many more pebbles of the quartzite are available than were measured, but from station Q downstream they are less numerous, and the study stopped of necessity with station W, 28.4 miles from station A, where a half-hour search on an extensive gravel bar revealed only two small quartzite pebbles. In all, 642 boulders, cobbles, and pebbles were measured. A few of the pebbles were collected for comparison with other rocks in the laboratory.

After the writer returned to the office, the necessary computations of the ratios $\frac{r_1}{R}$ and $\frac{r_2}{R}$ (p. 93) were made and the positions of the pebbles plotted on the double logarithmic charts described in the preceding paper (pp. 97-102). The result is shown in figure 38. The values of $\frac{r_1}{R}$ were then averaged for each station, and the curve shown in figure 39, A, was plotted. It will be noted that, although the points show a general trend, they do not lie very close to a smooth curve. The value of $\frac{r_1}{R}$ for the pebbles at a given station seemed to correspond not only to the hardness of different pieces of the quartzite but also to the size of the pebble. Instead of $\frac{r_1}{R} = f(\text{hardness})$ —that is, some function of hardness alone—the following is more nearly true:

$$\frac{r_1}{R} = f(\text{hardness}) \times f'(R)$$

Because the hardness or durability of the pebbles was for the most part unknown, the value of this factor had to be ignored in the hope that in the averaging of large numbers its effect would be smoothed out. The effect of size could still be studied, however. Preliminary to this study the value of $\frac{r_1}{R}$ for each of the 642 pebbles was corrected,

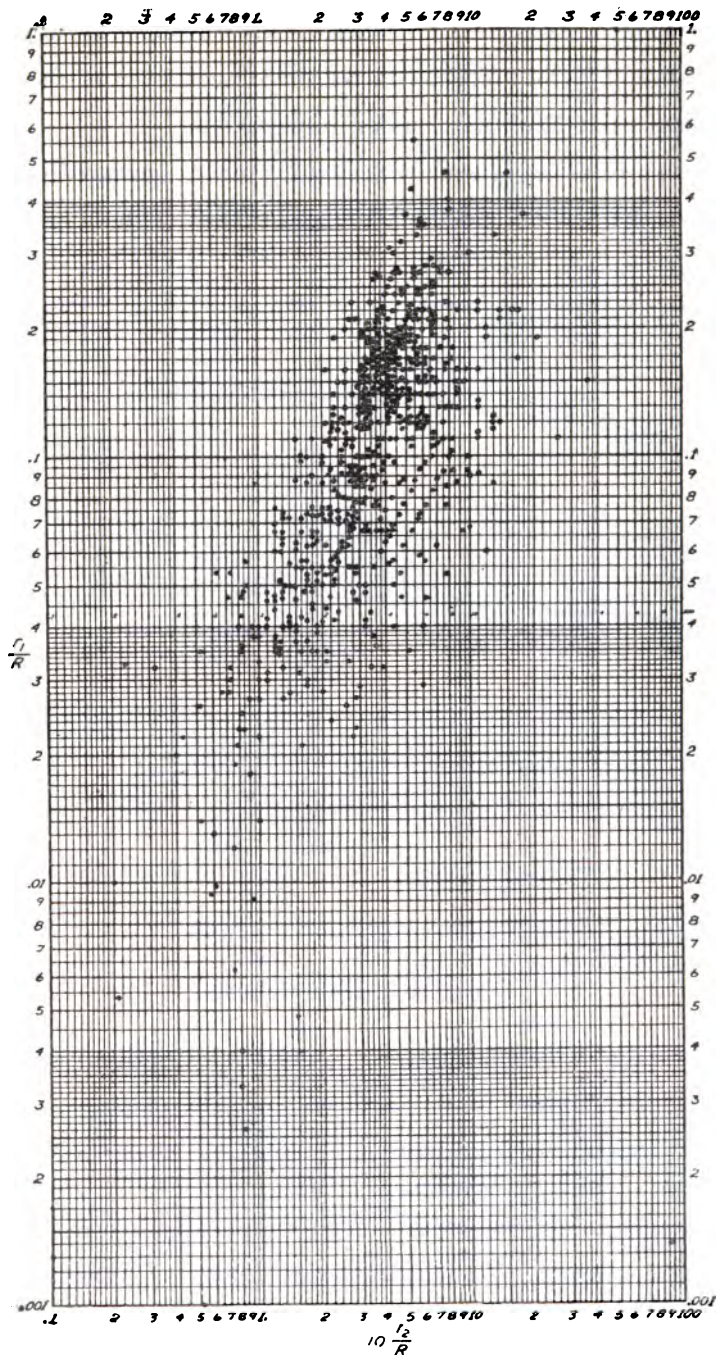


FIGURE 38.—Chart showing distribution according to shape of 642 river pebbles, cobbles, and boulders from Russell Fork of Big Sandy River, Va.

by the use of the curve of figure 39, A, to its corresponding value for a standard distance of 25 miles. This was done by multiplying each value of $\frac{r_1}{R}$ by a station factor, which consisted of the ratio of the ordinates at 25 and at x miles, respectively.

The new values of $\frac{r_1}{R}$ were then divided into 11 groups on the basis of size of the pebble, and the averages for each of these groups were

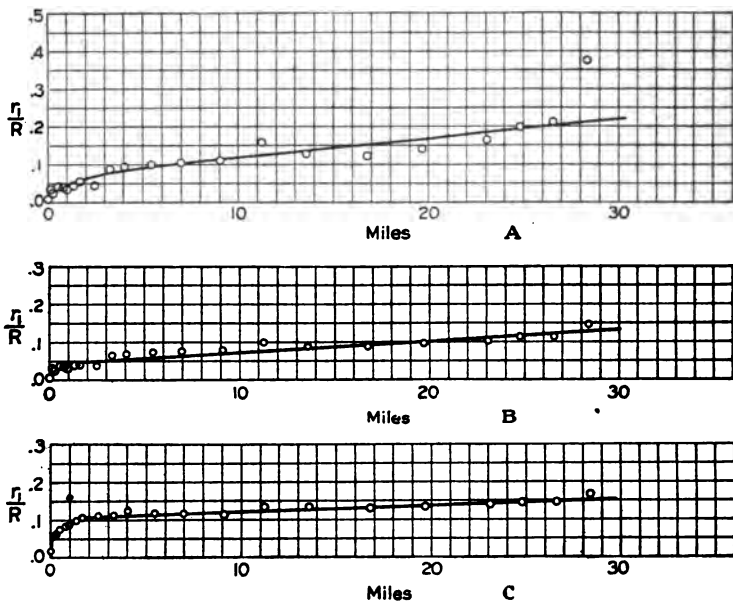


FIGURE 39.—Curves showing relation of roundness of pebbles to distance of transportation.

computed. These averages were plotted as shown in figure 40, curve a, where

$$\frac{r_1}{R} = 5.26 (2R)^{-1.15} + 0.133$$

was found to fit these points well. Curve b represents the values of $\frac{r_1}{R}$ on the assumption that r_1 , the radius of curvature of edges, is a constant regardless of the size of the pebbles, when the distance is the same. Curve c follows the alternative assumption that r_1 is proportional to the linear size of the pebbles and hence $\frac{r_1}{R} = \text{some constant}$ as shown. The form of the actual curve (a) shows that the latter assumption is more nearly true for a wide range of the large sizes.

As the diameter of the pebbles measured at most of the stations where the effect of size was critical ranged from 25 to 150 milli-

meters, and as the average size at the different stations varied somewhat, it seemed desirable to correct the original values of $\frac{r_1}{R}$ for size, and this was done on the basis of curve a of figure 40. From the corrected values curve B of figure 39 was plotted. It is seen to be much smoother than curve A. Finally, by plotting a curve of the relation of roundness to size for each station similar to that of figure 40, and correcting the values of $\frac{r_1}{R}$ by these curves instead of using curve a of figure 40 for all, a third set of roundness ratios was derived. These ratios were averaged, and curve C of figure 39 was plotted. This is believed to be the best curve derivable from these data. It is shown plotted on a greater vertical scale in figure 41. When

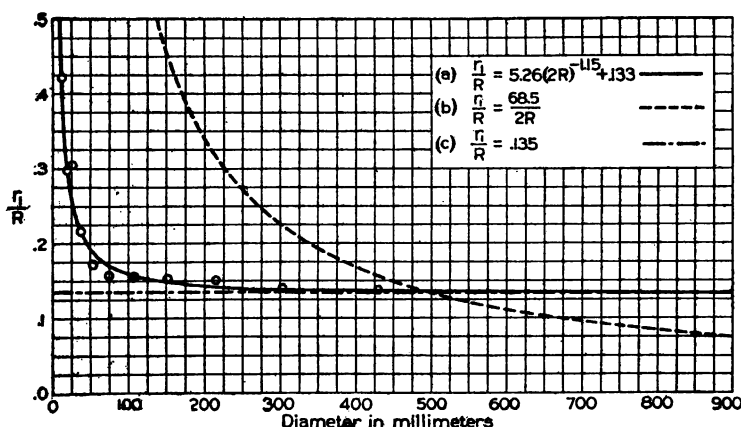


FIGURE 40.—Curves showing relation of roundness ratios to size of pebbles.

account is taken of the number of unknown variables that enter into the problem, aside from distance traveled and from the size, which have been approximately eliminated, this curve will be regarded as fairly satisfactory, in spite of two or three erratic points.

SIGNIFICANCE OF RESULTS.

The form of the curve of figure 41 is about what might be expected, except that the transition from the rapid rounding represented by the steep part to the more gradual change represented by the flatter part is more abrupt than would be anticipated. It seems probable that the steeper part of the curve represents the rounding of edges by spalling of corners and that the flatter part represents the slower rounding by a grinding process, spalling being very rare after a certain degree of rounding has been reached.

Interpretation of the form of this curve is vitiated to some extent by the changing of gradient and consequently of violence of trans-

portation, which the writer has called "rigor," from one part of the stream to another. The form of curve showing the relation of rounding to distance with a constant rigor was investigated experimentally by subjecting angular pieces to abrasion in a tumbling barrel. The general arrangement of the apparatus is shown in Plate XV, *C*. The barrel is driven at a rate of about 33 revolutions a minute. The inside is lined with wood, and the abrasion is due entirely to the action of a certain definite number of grinding pebbles on the pebbles that are being studied. A continuous stream of water is fed into the barrel, and the abrasion takes place partly under water and partly above. The grinding pebbles are renewed frequently so as to maintain a nearly constant size. The results of the study of rounding under conditions of constant rigor are shown

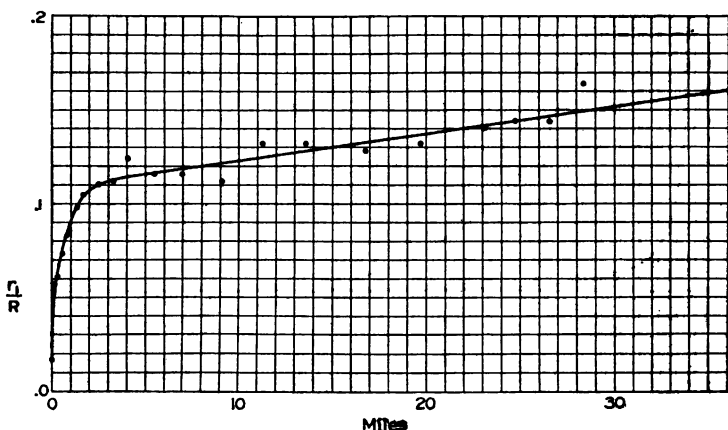


FIGURE 41.—Final curve of rounding of pebbles with respect to distance traveled.

in figure 42, in which the field curve from figure 41 has been redrawn, the values of $\frac{R_1}{R}$ as determined experimentally plotted, and the dotted experimental curve drawn. The rate of abrasion in the barrel is not the same as that in the stream, so that it was necessary to change the horizontal scale of the experimental curve by a constant factor to match the two curves at $x=29$ miles. As it is the form rather than the scale of the curve that is significant in this connection, this change is quite permissible.

The similarity of the curves is striking, amounting practically to identity for a considerable part of their length. The differences may easily be accounted for by lack of uniformity of rigor in the stream. In the steeper head portion of the stream the curves are practically the same; from $x=2$ miles the stream is less effective in rounding than the curve of constant rigor calls for, and the effectiveness diminishes to the end of the course. It is very suggestive that there

is an inflexion in the stream profile at about 14 miles, and the gradient increases as The Breaks are approached. Beyond pointing out the apparent significance of this relation, it is not possible at present to correlate stream rigor and stream gradient, for the rigor probably varies with sizes of pebbles transported and with many other factors not yet determined.

To enable the reader to visualize the data presented in graphic form, the general shapes and degrees of rounding noted will be described. At the head of the stream the fragments are sharp-edged. As the stream was followed the gradual rounding of the edges was clearly noticeable, even without making measurements. The surfaces of the pebbles are smooth and show some polish. At the lower stations the pebbles are moderately well rounded, though the original

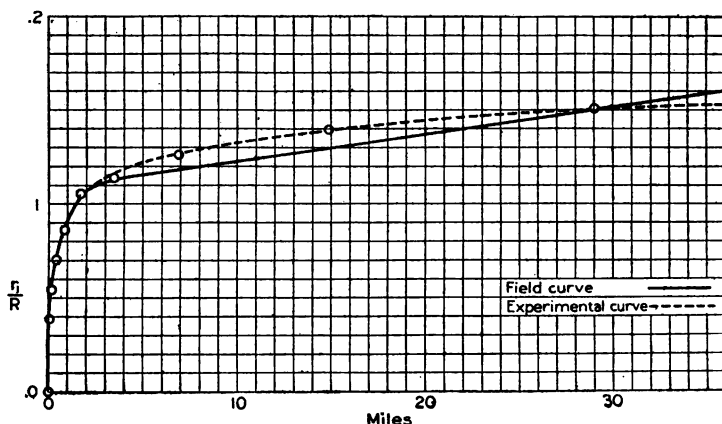


FIGURE 42.—Comparison of curves of rounding of pebbles with respect to distance traveled obtained by field and experimental measurements.

form still persists in its essential outlines and only the corners and edges are greatly changed. None of the pieces have nearly the roundness or symmetry of an egg, or even that of an average potato. The total loss of weight, as deduced from the change in shape and experimental studies, averages about 6 per cent. A few of the pebbles or cobbles show evidence of fresh breaks and of shapes resultant from fracture subsequent to their removal from the head of the stream. This phenomenon was sufficiently rare to be noticeable in comparison with the shapes of most of the pebbles derived by abrasive work only from the original angular form.

As has been pointed out above, the abrasion in the tumbling barrel varies widely with the number and size of pebbles used in it, and it can not be employed by itself as a measure of the distance necessary to form rounded pebbles under natural conditions. Bonney³ has called attention to this fact and to the inadequacy of such methods to

³ Bonney, T. G., Observations on the rounding of pebbles by Alpine rivers: *Geol. Mag.*, dec. 3, vol. 5, pp. 54-61, 1888.

determine the rate of rounding. He went further, however, and concluded that the abrasion of angular blocks in a revolving cylinder is not of general application because the only sort of river work similar to it is the abrasion of pebbles in potholes. This conclusion the writer can not accept, because the comparison here made of the forms of the field and experimental curves proves conclusively the essential similarity of the field and experimental processes for streams of the general type of Russell Fork. It is true that in the tumbling barrel the work done is almost pure abrasion and impact, whereas in the stream there are in addition the effects of weathering, such as cracking, crumbling, and spalling off of flakes, during the delays in transit. The importance of these factors can not be stated until further studies have been made. It is apparent, however, from a comparison of the two curves in figure 42 that the results, so far as shaping is concerned, are closely similar to those of the experimental studies. The method of the tumbling barrel therefore seems to be of far wider application than has heretofore been thought, and it needs only to have its rate determined by comparative measurements in streams of different sorts to become of considerable value.

One of the most valuable applications of the roundness-distance curve is in determining the distance certain pebbles have traveled by a measurement of their roundness. A gage of the reliability of such a method may be obtained by assuming that the distance is unknown for each of the station groups in the Russell Fork study and determining the distance by use of the mean roundness on the curve of figure 41. Comparison of distance thus determined with the actual distance will give the error of such a determination. The average error for all the stations, 21 in number, was found to be 24 per cent. The determinations for four of the stations were very erratic, owing, in part at least, to the use of a small number of pebbles—only two at one station. With these four stations omitted, the average error was only 11 per cent.

It must be understood that this figure represents only the error due to variation of hardness and of individual history at each of the stations, the perfection of the curve as drawn being assumed. Other factors that would affect such a determination for material from other streams are as follows:

1. The comparative rigor of the type stream and the unknown stream will affect the ratio of roundness to distance very considerably. The larger features of relation between gradient and load, on the one hand, and rigor, on the other, can be investigated by combined field and laboratory study.

2. The comparative durability of the pebbles of the stream used for the type curve and of those whose distance of travel is to be determined can easily be ascertained experimentally.

3. The effect of original shape can be largely investigated experimentally.

4. The effect of nonhomogeneous structure, schistosity, etc., can also be evaluated to a large extent experimentally.

Grabau ⁴ gives tables showing the distance pebbles of a certain size and material are carried before being obliterated, but he does not state what method was used in obtaining these results. On the basis of the amount of abrasion the Russell Fork quartzite has undergone in 28.4 miles and the relative rates of loss by abrasion for different sizes,⁵ the writer has computed the distance necessary to reduce a 50-gram angular piece of quartzite to a pebble of one one-hundredth the initial weight—that is, 0.5 gram. The result is approximately 400 miles. This computation was made on the assumption of constant rigor, the same in amount as the average of the upper 28.4 miles of Russell Fork. For smaller pebbles, carried farther downstream, it is reasonable to suppose that the rigor becomes very much less and that the estimate of 400 miles is much too low.

Though some of the above-mentioned factors are still unknown, the writer has deemed it worth while for the sake of discussion to deduce by this method the distance of travel for pebbles of vein quartz taken from the Lee conglomerate, of Pennsylvanian age. These were collected at Big Stone Gap, Va., and measured in the manner described. They were found to be as round as the Russell Fork pebbles of the same size which had traveled 16.5 miles. The durability of the Lee pebbles, however, with respect to abrasion was found experimentally to be approximately three times as great as that of the quartzite pebbles of Russell Fork. The distance of travel for the Lee pebbles, if conditions of similar kind and rigor are assumed, is 3×16.5 , or about 50 miles. This estimate is of course subject to wide revision when further studies throw light on other conditions of transportation in streams or otherwise and the interpretation of such conditions by a study of shapes becomes possible.

A determination of the roundness of limestone pebbles from a supposed intraformational limestone conglomerate in the Black Hills of South Dakota has been made by Miss Fillman.⁶ The average of measurements on 90 of these pebbles indicates a roundness equal to that shown by quartzite pebbles on Russell Fork at 0.45 mile. The limestone pebbles were found by abrasive tests to be only one-thirteenth as durable as the quartzite, and from this ratio the equiva-

⁴ Grabau, A. W., *Principles of stratigraphy*, p. 247, 1913.

⁵ Wentworth, C. K., *A laboratory and field study of cobble abrasion*: Jour. Geology, vol. 27, fig. 2, 1919.

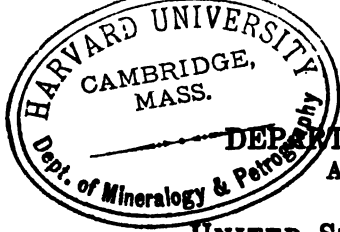
⁶ Fillman, L., *On the so-called limestone conglomerate of the northern Black Hills of South Dakota* (unpublished thesis, State University of Iowa, 1921).

lent travel under the same conditions was derived as approximately 0.035 mile, or slightly less than 200 feet. These limestone pebbles are for the most part flat and lozenge-shaped, though not very symmetrical. It is impossible, in the light of present knowledge, to make any definite statements as to what were the stream or beach conditions under which these pebbles were rounded, and the figures given above furnish a statement only of the amount of abrasion they have sustained. More definite utilization of the measurements of these pebbles must wait until adequate data on the significance of the flat and elliptical shapes of pebbles found on some beaches are available.

An estimate was made by a similar method of the transportation and consequent abrasion necessary to remove striae from glacial pebbles. Plate XV, A, shows 11 striated pebbles from the vicinity of Afton Junction, Iowa. These pebbles were subjected to abrasion in the tumbling barrel until the striae were practically removed. Faint traces of the striae may still be seen on one or two of the pebbles, which were photographed after the abrasion (Pl. XV, B). The distance of travel, after taking account of the difference of rigor between the experimental conditions and those of the natural stream, was 0.35 mile. Though differing conditions in rigor would modify this figure, the results show how short is the travel necessary to obliterate the striae. The pebbles are still recognizable as glacial in origin by their facets, though not so conclusively as before. Some of these pebbles were hard limestone and others a fairly compact greenstone.

The above estimates indicate very imperfectly some of the interpretations which may be made very much more accurately later, when the evaluation of more of the unknown factors has been accomplished. The writer hopes to be able by further field and laboratory work to make additional studies of this subject. Localities where rocks of easily identifiable types crop out in clearly defined areas and furnish to streams pebble material which can be distinguished from local rocks are necessary for further studies. Suggestions in regard to such localities will be especially helpful.





JAN 13 1923

DEPARTMENT OF THE INTERIOR

ALBERT B. FALL, Secretary

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, Director

Bulletin 730—D

PHYSIOGRAPHIC PROVINCES AND SECTIONS IN
WESTERN OKLAHOMA AND ADJACENT
PARTS OF TEXAS

BY

NEVIN M. FENNEMAN

Contributions to the geography of the United States, 1922

(Pages 115-134)

Published December 20, 1922



WASHINGTON

GOVERNMENT PRINTING OFFICE

1922

CONTENTS.

	Page.
General features of the area	115
Physiographic provinces	115
High Plains section of the Great Plains	115
Osage section of the Central Lowland	116
Nature of the investigation	117
Problem of the "Plains Border"	117
Conclusions	118
Field work	119
Topography on the several formations	120
Formations recognized	120
Oklahoma part of area	120
Enid formation (Permian)	120
Pennsylvanian series	121
Formations above the Enid formation	121
Escarpment of Blaine formation	121
Sandstone beds of the Woodward formation	122
Greer and Quartermaster formations	123
"Red Beds" of uncertain relation	123
Texas part of area	124
Escarpment of Permian rocks near Throckmorton	124
Escarpments of Permian rocks near Aspermont	125
Peneplain in Texas part of the area	125
The "break of the plains"	125
Some principles of erosion in arid climates	126
Gullies in general	126
Lack of branching in gullies of arid regions	127
Percolation of surface water as a factor	127
Wind as a factor	127
Sapping	128
Flat bottoms	128
Depth of the draw	128
Terraced draws	129
Larger valleys	129
Stratum plains	130
Special conditions of valley cutting in scarped plains	131
Aggrading streams	131
Summary of physiographic features and history	132
Relief	132
Streams	133
Indications of more than one cycle of erosion	133
Hypotheses respecting former base-leveling	133

ILLUSTRATIONS.

	Page.
PLATE XVI. <i>A</i> , Eastern escarpment of the High Plains, Hall County, Tex.; <i>B</i> , Peneplain on Enid formation southwest of Alva, Okla.; <i>C</i> , Sand dunes near Cimarron River, Woods County, Okla.; <i>D</i> , Fixed dunes near Cimarron River, Woods County, Okla.-----	120
XVII. <i>A</i> , Relief on stronger sandstones of Enid formation near a larger valley, western border of Grant County, Okla.; <i>B</i> , Relief on Greer formation near a larger valley, northern border of Dewey County, Okla.; <i>C</i> , Sink holes in Gypsum escarpment, 4 miles west of Shamrock, Wheeler County, Tex.-----	122
XVIII. <i>A</i> , Prairie Dog Fork of Red River, Hall County, Tex.; <i>B</i> , Gully with receding escarpments, Grant County, Okla.; <i>C</i> , Old valley rejuvenated, north of Chickasha, Okla.---	126
FIGURE 43. Index map of western Oklahoma and adjacent parts of Texas -----	117
44. Physiographic sections in western Oklahoma and adjacent parts of Texas as revised.-----	119

NOTE.—The Geological Survey's annual volumes entitled "Contributions to the geography of the United States" are issued in parts, and the last part will include a volume title-page, table of contents, and index for the use of those who may wish to bind the separate parts. A small edition of the bound volume will also be issued, but copies can not be supplied to those who have received all the parts.

PHYSIOGRAPHIC PROVINCES AND SECTIONS IN WESTERN OKLAHOMA AND ADJACENT PARTS OF TEXAS.

By NEVIN M. FENNEMAN.

GENERAL FEATURES OF THE AREA.

Physiographic provinces.—The area here considered is a part of the interior plains of the United States, which is an extensive region of relatively slight relief and nearly horizontal beds of rock that is divided between the Great Plains province, its western part, and the Central Lowland, its eastern part. The boundary between these two physiographic provinces runs in general southward and lies not far from the one hundredth meridian—the meridian that forms the eastern boundary of the Texas “panhandle.”

The most obvious difference between the Great Plains and the Central Lowland is one of altitude, for the plains are generally about 2,000 feet above sea level near their eastern edge and increase in height toward the west, whereas the lowland is everywhere below 2,000 feet. The boundary line between the provinces throughout most of its extent is drawn at the foot of an escarpment, or at least at the foot of an eastward slope, which is steeper than the average slope from the Rocky Mountains to Mississippi River. At some places it is clear that the lowland is expanding westward by continued erosion and that the escarpment which separates the plains and the lowland is retreating westward, and it is therefore evident that the lower surface of that part of the Central Lowland has been produced by the wearing down of the Great Plains, which formerly extended farther east.

Both the Great Plains and the Central Lowland may be divided into sections that differ somewhat in topography. Those represented in this area are the High Plains section of the Great Plains and the Osage section of the Central Lowland.

High Plains section of the Great Plains.—The High Plains are remnants of a once continuous plain whose surface was formed of Tertiary silt, sand, and gravel. This plain stretched from the Rocky

Mountains eastward beyond the present limits of the Great Plains, at a slope of not more than 10 feet to the mile. This once broad belt has been narrowed by erosion on both sides and is crossed from west to east by a few rivers, which have cut deep valleys, but the remnants of the original plain still dominate the landscape in the belt that is called the High Plains section.

These plains are typically exemplified in the Texas "panhandle," which lies along the western margin of the area herein described. Their treeless surface is essentially flat except for some valleys eroded near their eastern edge and near the large streams. They include also some wide, shallow depressions, some of which contain lakes, but none of these features are sufficiently pronounced to offset the general impression of flatness.

Generally along the eastern edge of the High Plains section there is a steep slope down to the Central Lowland. Throughout much of its extent this steep slope is an actual escarpment—the "break of the plains"—300 to 600 feet high, at some places straight, at others made irregular by the erosion of streams that head in the plateau and flow eastward.

Osage section of the Central Lowland.—The southwestern part of the Central Lowland, known as the Osage section, shows throughout its extent the character of a surface produced by degradation. The formations dip slightly toward the west or northwest and have been planed off, so that their edges crop out in belts that trend nearly southward. The outcropping edges of the more resistant members give rise to eastward-facing escarpments, which are generally 50 to 200 feet high. All these escarpments have been more or less dissected, some of them so much that hilly belts several miles wide have taken the place of what may once have been simple escarpments. On the intervening less resistant formations, most of them composed of shale, are broad, smooth surfaces. The alternation of these two types of topography is sufficiently common to suggest the term "scarped plains," which is often applied to the Osage section.

Several of the escarpments are exceptionally high and rugged. One, between Cimarron and Canadian rivers, in western Oklahoma, which marks the outcrop belt of the Blaine formation (fig. 43), extends from the Kansas boundary southeastward halfway across the State and is the most prominent of the several hilly tracts bearing the name Gypsum Hills. The other high escarpments lie mainly in Texas and die out toward the north in the vicinity of Red River. The highest and most rugged of these escarpments, which is made by beds of resistant limestone, lies a little west of the ninety-ninth meridian. Although these escarpments contrast strongly in topography with the smooth plains on either side, they belong to the same

general class with others in the Osage section of the Central Lowland, as the surface west of them is not very different in general character from that on the east.

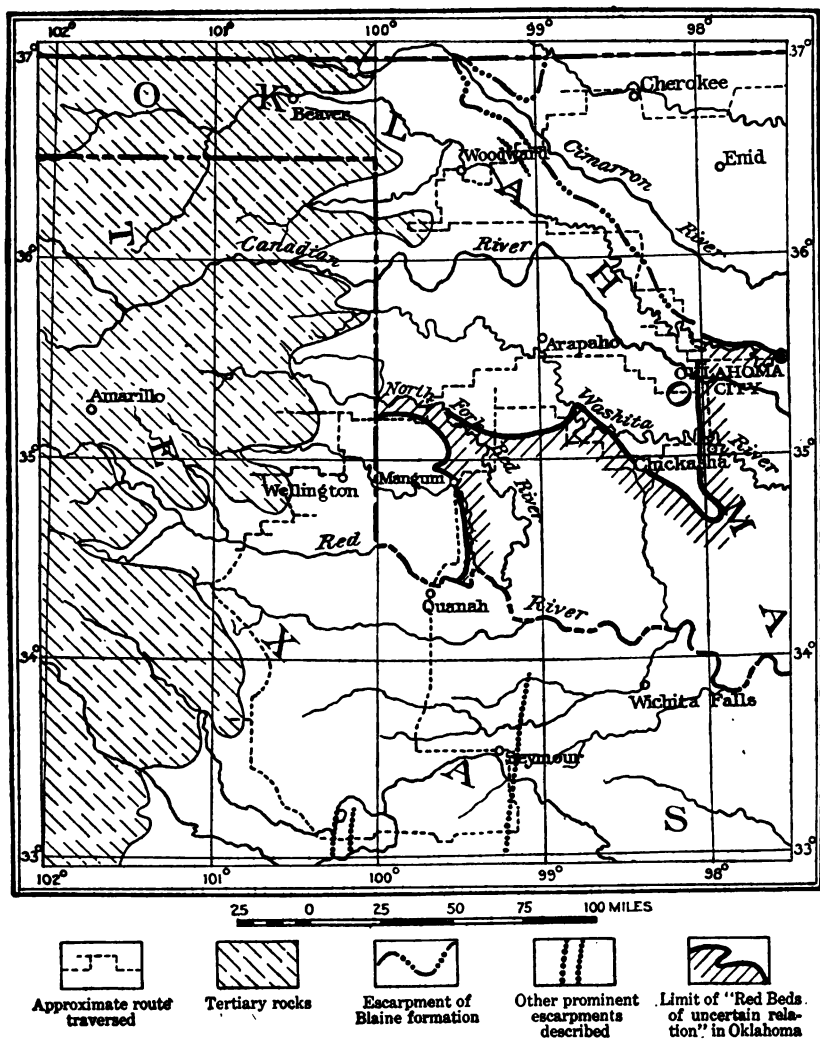


FIGURE 48.—Index map of western Oklahoma and adjacent parts of Texas.

NATURE OF THE INVESTIGATION.

Problem of the "Plains Border."—The study described in this paper concerns the character of the country just east of the High Plains. It has been assumed by geographers that a strip 25 to 75 miles wide, characterized by a rougher surface, intervenes between the High Plains and the typically developed Central Lowland. This

strip has been called the "Plains Border" and classed as a section of the Great Plains province. It has been defined as follows:

Consider these plains [the High Plains in their original extent] to have been a uniform smooth surface stretching from the mountains to eastern Nebraska and Kansas. The central strip or High Plains [section] is what is left of this flat surface, still covered by the late Tertiary beds to which the flatness is due. The Plains Border is the strip on the east from which the Tertiary mantle has been in large part eroded and which is now dissected but not reduced to the low relief which characterizes the Central Lowland. It is in general a hilly country.¹

This description was written with immediate reference to the part of the province lying in the latitude of Kansas. From the scanty physiographic information available for western Oklahoma and adjacent parts of Texas it was inferred that a similar division of the Great Plains province was applicable also to that region.

In the paper cited above it was assumed that the eastern front of the Gypsum Hills from the Kansas boundary to central Texas constitutes a fairly definite boundary between the typical lowlands of the Osage section on the east and a rougher region, less perfectly base-leveled, on the west. It was to test this assumption that the field investigation here recorded was undertaken. The question to be answered was: Should a distinct physiographic section be recognized between the High Plains and the Central Lowland in western Oklahoma and northern Texas?

Manifestly the boundary between a high plain and a continuous low plain can nowhere be merely a line, even if so represented on a map, and it must therefore be assumed that the two are separated by at least a narrow transitional belt, roughened by dissection but not base-leveled, even if such a belt has not been specifically mentioned. The propriety of treating this rougher strip as a distinct physiographic section depends partly on its width.

Conclusions.—It may be stated in advance that the result of the field investigation has led to the conclusions that the lower area next east of the High Plains has a generally uniform character from east to west and that it should not be divided and its parts allotted to different provinces. It is also doubtful whether any contrast between its eastern and western parts is sufficient to justify the setting up of two sections. Future detailed studies will probably enable the physiographer to recognize several divisions of a lower order, and in delimiting these divisions the minor scarps should doubtless be considered. The provinces and sections, as revised through this investigation, are shown in figure 44, in which the name "Smoky Hills section" is applied to what remains of the "Plains Border."

¹ Assoc. Am. Geographers Annals, vol. 6, p. 70, 1917.

Field work.—The field work underlying this study was a reconnaissance by automobile made in five weeks beginning June 15, 1921. The writer, assisted by Waldo S. Glock, followed a zigzag course (fig. 43) across the belt from northern Oklahoma to the parallel of 33° in Texas, about 100 miles south of Red River. The total distance traveled was approximately 1,450 miles, two-thirds of it in Oklahoma. The course followed led from Pawhuska, in Osage County, westward to the Gypsum Hills west of Alva; thence south and west to Arnett, on the High Plains in Ellis County; thence



FIGURE 44.—Physiographic sections in western Oklahoma and adjacent parts of Texas, as revised.

east beyond the Gypsum Hills in Blaine County; thence to Watonga and El Reno, crossing that line of Gypsum Hills three times; from El Reno south beyond Canadian River and northwest and west to Clinton, on the Washita; thence southwest across the North Fork of Red River and west to McLean, on the High Plains, in Gray County, Tex. The southward course in Texas lay not far from the High Plains escarpment as far south as Dickens County; thence southeast and east to Throckmorton County; thence in a zigzag line north and west to Quanah, Tex., and Eldorado, Okla. On the return trip through Oklahoma the course lay north to Mangum, in Greer County, and northeast over the flat plains among the out-

lying granite knobs of the Wichita Mountains; thence, after a northward detour over the more rolling surface of Washita County, east to Anadarko and Chickasha, north to El Reno, and east to Oklahoma City. The work was necessarily of reconnaissance character and insufficient to justify a full discussion of the physiography of the region, but the above outline of the route will enable those who are familiar with any of the broad areas that lie between the lines traversed to judge whether it is adequate and representative.

TOPOGRAPHY ON THE SEVERAL FORMATIONS.

FORMATIONS RECOGNIZED.

There is no marked contrast between the eastern and western parts of the area traversed with respect to the presence of nearly flat surfaces interpreted as remnants of a peneplain. The extent and flatness of such surfaces differs somewhat with the character of the underlying rock. The following formations are recognized in the area described:

Oklahoma:

Tertiary.

Permian:

Quartermaster formation.

Greer formation.

Woodward formation.

Blaine formation.

Enid formation.

Pennsylvanian.

North-central Texas:

Later Cenozoic.

Comanche (Lower Cretaceous).

Triassic (Dockum formation).

Permian:

Double Mountain formation.

Clear Fork formation.

Wichita formation.

Pennsylvanian.

The United States Geological Survey correlates the Double Mountain formation of Texas with the Greer and Quartermaster formations of Oklahoma, the Clear Fork formation of Texas with the Enid, Blaine, and Woodward formations of Oklahoma, and the Wichita formation of Texas with the Chase, Wellington, and Marion formations of Kansas.

OKLAHOMA PART OF THE AREA.

ENID FORMATION (PERMIAN).

In Oklahoma the Enid formation is noteworthy for its great thickness² of shale and weak sandstone and a relative absence of escarpment-making beds. It therefore forms the substratum of a wide belt of very low relief in middle Oklahoma.³ (See Pl. XVI, *B*.) There are, however, minor escarpments or hilly belts (Pl. XVII, *A*)

² C. N. Gould (U. S. Geol. Survey Water-Supply Paper 148, p. 44, 1905) estimates the thickness as 1,200 to 1,500 feet.

³ George I. Adams (Physiographic divisions of Kansas: Am. Geog. Soc. Bull., vol. 34, p. 95, 1902) calls this the Oklahoma Prairie.



A. EASTERN ESCARPMENT OF THE HIGH PLAINS, HALL COUNTY, TEX.



B. PENEPLAIN ON ENID FORMATION SOUTHWEST OF ALVA, OKLA.



C. SAND DUNES NEAR CIMARRON RIVER, WOODS COUNTY, OKLA.



D. FIXED DUNES NEAR CIMARRON RIVER, WOODS COUNTY, OKLA.

within the area of outcrop of the Enid formation, especially on the east side. Farther south in Texas the rocks are less uniformly weak, the escarpments are more pronounced, and the peneplain is less perfect.

PENNSYLVANIAN SERIES.

The Pennsylvanian series farther east and the higher formations of the Permian series farther west include beds of more unequal resistance to erosion. In southeastern Kansas and northeastern Oklahoma the Pennsylvanian underlies the most typical portion of the Osage section of the Central Lowland. This portion consists of belts of peneplain trending east of north, separated by escarpments, or narrow hilly belts, in each of which the general level rises westward by 50 to 200 feet. The whole region, therefore, resembles a stairway in which the risers are measured in feet and the treads in miles.

FORMATIONS ABOVE THE ENID FORMATION.

The surface on the higher Permian formations to the west is less smooth than that on the Enid formation. Aside from features due to aridity, it is more like that of northeastern Oklahoma. The general aspect is that of a peneplain, with the differences mentioned below. The plain is quite as perfect on the west side as on the east. Flat areas within sight of the Tertiary escarpment are as large and as flat as those near the Enid. (See Pl. XVI, *A* and *B*.) Several escarpments are noteworthy.

Escarpment of Blaine formation.—The Enid formation is overlain by the Blaine formation, which occupies the belt next west of it in northern Oklahoma. The Blaine is 75 to 100 feet thick and is the most prominent gypsum-bearing formation in the State, and its outcrop belt, almost throughout its length, forms a pronounced escarpment known as the Gypsum Hills or "Gyp" Hills. This escarpment is in places deeply and sharply dissected, producing a belt of rugged country that ranges in width from a fraction of a mile near El Reno to 4 or 5 miles along Cimarron River in the northwestern counties of the State. When this escarpment is approached from the east in northern Oklahoma, it appears to be a well-marked physiographic boundary. Moreover, within a few miles west of it, at least in places, there is another marked escarpment. As the distance between the Blaine escarpment and the edge of the High Plains is here only 30 to 60 miles, as the rise across the strike is about 16 feet to the mile, and as the intervening belt is traversed by one major valley (North Fork of Canadian River) and contains abundant sand dunes, it will be seen that if this part of the State alone were considered, there would be some justification in regarding

this line of the Gypsum Hills as the western limit of the Central Lowland.

The "break of the plains" here trends southwestward and the Blaine escarpment trends southeastward, so that, owing to this divergence, only a short distance to the south the two are separated by an interval of more than 100 miles. The surface of the wide belt between them differs but slightly in character from that of the plain east of the Blaine escarpment, which, moreover, disappears north of El Reno, in latitude $35^{\circ} 30'$, leaving the so-called Plains Border without a natural boundary on the east for the remaining two-thirds of its length in Oklahoma and Texas.

Sandstone beds of the Woodward formation.—The Permian formations that underlie the surface west and south of the Blaine escarpment are fairly uniform in physical character, consisting mainly of red shale and sandstone. In their effect on topography they afford no contrast and offer no suggestions as to the division of the area into physiographic units. The most conspicuous escarpment maker in the Woodward formation is the Whitehorse sandstone member. In eastern Woodward County, several miles west of Quinlan and only 5 or 6 miles west of the Blaine escarpment, this sandstone forms a rugged escarpment more than 100 feet high, sharply dissected by young valleys, some of them 100 feet deep. This member is described⁴ as forming conspicuous buttes and mesas 100 to 200 feet high from Kansas southward beyond Washita River to latitude 35° . These rugged, angular hills of intensely red sandstone give a striking character to the landscape and, so far as they go, would justify the recognition of the area in which they occur as a distinct physiographic unit, but they are relatively isolated. The observer need only turn his back on them to see broad, flat, or gently rolling surfaces, indistinguishable in topography and vegetation from the peneplain on the Enid formation. Not only do the buttes, mesas, and escarpments occupy a minute proportion of the total surface, but the area within which such features are in view is, by comparison, insignificant.

In southern Kansas the Whitehorse sandstone member is an important element in the great escarpment which lies at the edge of the High Plains in their long eastward extension within the "big bend" of Arkansas River. The dissection of that escarpment has made the Red Hills. At the south, in Oklahoma, this escarpment, together with that of the Blaine formation, turns northwestward along the Cimarron to make the narrow V whose sides face each other across that river. Farther south, toward Watonga, El Reno, and

⁴ Aurin, Fritz, *Geology of the red beds of Oklahoma*: Oklahoma Geol. Survey Bull. 30, p. 28, 1917. Most of the localities of buttes and mesas described by Aurin have been seen by the writer.



A. RELIEF ON STRONGER SANDSTONES OF ENID FORMATION NEAR A LARGER VALLEY, WESTERN BORDER OF GRANT COUNTY, OKLA.



B. RELIEF ON GREER FORMATION NEAR A LARGER VALLEY, NORTHERN BORDER OF DEWEY COUNTY, OKLA.



C. SINK HOLES IN GYPSUM ESCARPMENT, 4 MILES WEST OF SHAMROCK, WHEELER COUNTY, TEX.

Chickasha, the rugged aspect of the escarpment is less marked, but the sandstones of the Woodward formation tend to maintain a slight elevation above the surrounding country, as in Blaine County; or to give a more sharply rolling character to the divides, as between North Canadian and Canadian rivers west of El Reno; or to make high, bold bluffs now subject to revived erosion, as east and west of Anadarko.

Greer and Quartermaster formations.—The topography on the Permian formations above the Whitehorse sandstone, as recognized by the Oklahoma Geological Survey,⁵ is for the most part rolling rather than flat (Pl. XVII, *B*), but there are also broad areas of approximate flatness. So far as seen by the writer, such flat areas are more marked and extensive farther west in the "panhandle" of Texas.

"RED BEDS" OF UNCERTAIN RELATION.

The descriptions thus far given apply to that part of the area considered that lies north of the thirty-fifth parallel. On the Oklahoma geologic maps a large area surrounding the Wichita Mountains appears as "Red Beds of uncertain relation." It might well be inferred that the reason for this uncertainty is to be found in the weakness of the rocks and a consequent lack of outcrops, the surface being therefore one of low relief. This inference as to topography agrees with the facts as described by Taff⁶ and as observed in the reconnaissance by the writer. On the west side of the Salt Fork of Red River, which flows south in Harmon and Jackson counties, are some bluffs, mesas, and uplands that rise more than 200 feet above the stream. The escarpments contain prominent beds of gypsum and sandstone. West of these escarpments the relief is less and the rolling surface merges into a broad peneplain. East of Salt Fork is the wide low plain that surrounds the Wichita Mountains and their outlying granite knobs. This plain east of the North Fork is coextensive with the area designated on the geologic maps of Oklahoma "Red Beds of uncertain relation." From 6 to 10 miles north of the Chicago, Rock Island & Pacific Railway this plain abuts on the north against a higher rolling surface marked on the geologic maps as occupied by the Greer formation. On its east side the plain in like manner ends against the long southeastward extension of the Greer formation, the surface of which is more strongly rolling.

If this locality alone were considered the line of contact shown on the geologic map might perhaps be used as a boundary for physio-

⁵ See map, Oklahoma Geol. Survey Bull. 11, p. 128, 1913.

⁶ Taff, J. A., Preliminary report on the geology of the Arbuckle and Wichita mountains in Indian Territory and Oklahoma: U. S. Geol. Survey Prof. Paper 31, pp. 72-74, 1904.

graphic subdivisions, but the contrast in physiographic character is probably too small to justify divisions so important as sections. Moreover, as already mentioned, the sharp relief just west of this boundary is of very slight extent and is not representative of a broad area.

TEXAS PART OF AREA.

Escarpment of Permian rocks near Throckmorton.—The Permian rocks change in character remarkably both northward and southward from central Oklahoma. In both directions the red color disappears and the thick beds of shale and generally weak sandstone give place to shale and limestone. Different sets of formations are recognized in Oklahoma and in Texas (see p. 120), and the correlation of the two sets is not finally determined.

In Texas escarpments appear along horizons not thus marked in Oklahoma. Some of them, if extended northward along the strike, would cross the low plains on the "Red Beds of uncertain relation" around the Wichita Mountains. Others would appear in the more strongly rolling surface to the east or to the west.

The easternmost of these escarpments in Texas seen by the writer lies a little west of the ninety-ninth meridian. (See fig. 43.) It trends slightly west of south and passes the villages of Throckmorton and Albany. In places it consists of several rather than a single escarpment, and it becomes higher and more ruggedly dissected toward the south, where its total height is 150 to 250 feet, but on the north it dies out in a wide sloping belt near Red River. The belt of dissected escarpments near Throckmorton (the southernmost place reached on the trip) is at least 10 miles wide.

This series of escarpments is produced by resistant limestone beds in the upper part of the Wichita formation.¹ East of it lies an "irregular rolling surface of moderate relief,"² the southward extension of the flattest part of the Osage section in Oklahoma. Farther east are the lower sandstone escarpments of the Pennsylvanian formations. Approached from the east the change in physiographic character at the rough limestone escarpment near Throckmorton is impressive, but this rugged belt can not well be used as a physiographic boundary except for units of a smaller order than sections. In the first place, it dies out at the north in the midst of a wide plain; in the second place, it is succeeded on the west by plains 30 to 40 miles wide, broken only by intrenched streams that have begun anew to erode their valleys—features which, though to a less extent, appear in the rolling plain east of the escarpment and are not uncommon in the

¹ Gordon, C. H., *Geology and underground waters of the Wichita region of north-central Texas*: U. S. Geol. Survey Water-Supply Paper 317, p. 8, pl. 1, 1913.

² *Idem*, p. 8.

flatter parts of central Oklahoma, even in the lowlands on the Enid formation.

Escarpments of Permian rocks near Aspermont.—West of Throckmorton plains extend completely across Haskell County, a distance of 30 miles, and overlap into adjacent counties, where they abut against an 80-foot escarpment of gypsum and dolomite 6 miles east of Aspermont, in Stonewall County. This escarpment, with its companion 7 miles farther west, is the local representative of the "Gypsum Hills." It was not followed northward and southward, and data to show its exact correlation are not available. It may indicate the outcrop of the same beds that come to the surface at the western limit of the plains on the "Red Beds of uncertain relation" in Oklahoma. If so, there is here another line which might be used as a minor physiographic boundary. It is subject, however, to the same comment as the others, namely, that the landscapes on its two sides show little or no contrast.

Seven miles west of this escarpment is another, of about the same height, made by beds of gypsum and sandstone. Between the two escarpments is a strip of nearly flat plain in which lies the town of Aspermont.

Peneplain in Texas part of the area.—The top of the escarpment west of Aspermont affords a wide view of a peneplain which extends thence westward to the "break of the plains"—that is, to the relatively narrow strip of rough country which fringes the eastern edge of the Tertiary rocks. The distance across this peneplain is about 50 miles. The route followed leads northwestward to the towns of Spur and Dickens, in Dickens County.

The peneplain as observed in the first line of counties east of the High Plains (Kent, Dickens, Motley, Hall, Collingsworth, and Wheeler counties) compares favorably in its perfection with that seen on any other part of the route traversed in the two States, except that the Enid formation no doubt affords flat areas of greater extent, even if not flatter.

Here and there on this western part of the peneplain are buttes and mesas, much the most prominent of which is Double Mountain. Most of the others are close to the escarpments, of which they are outlying remnants. They impair the perfection of the peneplain much less than the intrenched streams. As stated above, these streams do not differentiate the area here considered from the Osage section, unless by the degree of their rejuvenation.

THE "BREAK OF THE PLAINS."

The escarpment at the eastern edge of the High Plains is generally clear, though not everywhere equally bold (Pl. XVI, A).

In only one of five counties in which it was approached or ascended in Texas does it fail to rise conspicuously on the western horizon. The exception is the northernmost county, Wheeler, in which it was approach at one place only. (See Pl. XVII, *C.*). At that place a rise of 500 feet is accomplished in about 10 miles west of the village of Shamrock, and throughout much of this distance sand dunes prevail. A semidetached eastward extension of the High Plains in Ellis County, Okla., north of Canadian River and the thirty-sixth parallel, shows a similar slope likewise dotted with sand dunes. Such gradation with lack of a definite escarpment will probably be found to be general between the thirty-fifth and thirty-seventh parallels.

The escarpment at the edge of the Tertiary area is most prominent where the Tertiary beds rest on resistant underlying rocks. In southern Kansas the escarpment is due to Cretaceous beds and Permian formations that have already been described. From the Kansas-Oklahoma boundary south to the thirty-fifth parallel, along the edge of the High Plains, Tertiary gravel rests on upper Permian formations, in which no strong escarpment-making members are known to the writer. It is not to be expected that this part of the High Plains boundary will be found to be as clear and distinct as other parts.

South of Red River the eastern edge of the High Plains coincides essentially with the outcrop belt of the Triassic Dockum formation and still farther south with that of the Cretaceous limestones. Udden^{*} states that the "North-Central Plains" are bounded "on the west by the high erosion escarpment of the Pan Handle High Plains and the Llano Estacado," thus implying the presence of an eastward-facing escarpment throughout the length of the High Plains in this area.

SOME PRINCIPLES OF EROSION IN ARID CLIMATES.

Some physiographic features of this region can not well be described in terms suited to conceptions of erosion in more humid climates or on rocks of other character; therefore, as a preliminary to the physiographic history of the region, a brief description of these forms and the processes by which they were made will be given. It is convenient first to consider the effect of erosion as illustrated in the smaller forms, beginning with the gully, and to proceed thence to larger features and the larger questions involved.

Gullies in general.—The physiographer's conception of the progressive dissection of peneplains, as of other plains, is based mainly on the growth of gullies. Rapid down cutting, steep sides, V-shaped cross section, and branching enter most abundantly into his mental

^{*} Udden, J. A., Review of the geology of Texas: Texas Univ. Bull. 44, p. 18, 1916.



A. PRAIRIE DOG FORK OF RED RIVER, HALL COUNTY, TEX.



B. GULLY WITH RECEDING ESCARPMENTS, GRANT COUNTY, OKLA.



C. OLD VALLEY REJUVENATED, NORTH OF CHICKASHA, OKLA.

pictures of an upland of homogeneous material or horizontal rocks that is undergoing dissection, especially when erosion is vigorous.

Lack of branching in gullies of arid regions.—The first modification of this conception is made necessary by the fact that many gullies in semiarid regions like the one here considered do not branch at all. Others show only incipient branches, so wide in proportion to their length that the gully wall is scalloped in a series of open alcoves. Gullies having walls retreating in this way have almost flat bottoms, many of them very wide. The flat bottom is not unknown in humid regions, nor is the V-shaped branching gully unknown in arid regions.¹⁰ "Badlands" are indeed commoner in arid than in humid regions, but the conditions favoring the development of the flat-bottomed "draw"¹¹ (Pl. XVIII, *B, C*) with retreating walls are more commonly associated with aridity than with humidity.

The suggestion that such forms are favored by alternate beds of different character and that they are the beginnings of stratum plains contains some truth but is inadequate. Two facts bearing on this point may be recalled—that such forms are common on the High Plains in the unconsolidated Tertiary formations, and that their flat floors may have a steep slope downstream, even though horizontal in cross section.

Percolation of surface water as a factor.—The absence of branching is no doubt due primarily to the dominance of percolation as opposed to run-off. Where all the water goes into the ground no channels form. A steep edge of homogeneous dense clay could not escape dendritic dissection. This factor of large percolation is more common in arid regions because of the dryness of the ground and the depth of the water table, but aridity is not essential.

Wind as a factor.—A second factor is the work of the wind. The drier the ground the more effective is the wind in filling incipient channels and erasing the effect of one rain before another comes. Long intervals between rains and scarcity of vegetation make wind more effective. As all gullies have small beginnings, it is not strange that in arid regions many incipient branches should be checked in their growth by the work of the wind and that some gully walls should retreat long distances without dissection.

¹⁰ Dutton, though stating that denudation in arid regions is accomplished largely by recession of cliffs rather than by down-cutting, lays stress on the fact that the Vermilion Cliffs, in the Grand Canyon region, are cut by numerous branching canyons (U. S. Geol. Survey Mon. 2, p. 62, 1882). From the writer's observations it would appear that, although such dissection affects the rate of recession, it is by no means the cause of the preponderance of lateral stripping over vertical down-cutting, nor is it going on in all areas that show lateral denudation.

¹¹ The word "draw" is frequently used on the Great Plains to designate a small, shallow valley, regardless of the form of its sides. The word is used here in the colloquial sense to designate such a valley that started as a gully but has become so wide that the application of the term "gully" would be misleading.

A consequence of this checking of gullies in their incipient stages is seen in the "coarse texture" of dissected plains in arid regions. Apart from the absence of trees, the casual observer thinks there is something typically "western" (arid) about the long, unbroken slopes of the Great Plains, where they are not flat.

Sapping.—However, why does the gully wall retreat, and why does it remain vertical? Manifestly the second condition depends on the first, as no cliff continues long to be vertical or even steep unless it does retreat. The manner of retreat is therefore the critical point.

In humid climates corrasion by direct run-off is the main factor in the development of most gullies, hence down cutting is dominant and widening and headward lengthening are merely incidental to down cutting. With increase of percolation, however, corrasion becomes much less effective, its effectiveness decreasing in geometric ratio to the decrease in the amount of run-off, and the lessened down cutting is accompanied by lessened lateral and headward growth of the gully. This is offset by sapping, as the percolating water that did not cut back the escarpment by corrasion accomplishes the same result by sapping at the base of the scarp.

Sapping, therefore, is the dominant factor in determining the form of the flat-bottomed, scarp-bordered gully or "draw" of arid regions. At some places landslides are effective, and where the underlying beds are shale mud flows may be a prominent or even the dominant factor in the development of scarps. Wind is no doubt one of the chief agents, if not the chief, in removing waste from the foot of the scarp and thus preventing the process of recession from becoming self-limited.

Flat bottoms.—With its limiting escarpments thus receding the tendency of the gully to become a flat-bottomed draw is apparent. Where drainage from a considerable area centers in the draw the preservation of the flatness of its bottom is surprising, and it seems a safe inference that in all such draws the amount of sediment fed to the stream during a freshet is greater than can be moved by the current, at least during the subsidence of the freshet. Hence any channel begun during the earlier stages of the flood is later obliterated by deposition. Almost all streams are "overloaded" during the subsidence of a flood, and even a gully in a humid region is apt to have a narrow sandy flat resting temporarily in the bottom of its V.

Depth of the draw.—The depth of the draw or the height of its walls—that is, the level at which the flat bottom is maintained—is controlled by a combination of factors, one of which is evidently the inability of the stream to transport all the débris supplied to it during the subsidence of freshets. The existence of nearly horizontal resistant beds that may act as local base-levels for the stream is

another, and less obvious factors are the depth of the water table and the state of the soil above the water table, especially with respect to its content of moisture and salts. It can not be assumed that the base of the escarpment is generally as low as the water table or that ground water issues along it in springs, as other factors help to locate the horizon of effective sapping. Arid soils contain abundant salts, which cement and indurate the soils more at some levels than at others, and they tend to concentrate in the upper soil and to accumulate and form "mortar beds" near the water table. Unequal vertical distribution of this cementation may be an important factor in determining the horizon of sapping in an otherwise homogeneous formation.

Terraced draws.—It is not uncommon to find a new gully furrowing the floor of a wide, flat-bottomed draw. At first sight this might be interpreted as indicating a new cycle of erosion. It should be remembered, however, that conditions of the same sort as those which preserved the original surface from dendritic dissection, though in an exposed position and above its local base-level, may for a long time preserve the new flat at the bottom of the draw. When, with the development of the valley, the time comes to cut the bed of the stream down to a new level, the same process may be repeated, and thus flat after flat may be formed more or less rhythmically without any change in the regional base-level. No doubt, also, minor or temporary climatic changes or changes in vegetation cause many newly made valleys to be aggraded and degraded again within short periods.

Larger valleys.—The discussion has thus far concerned itself with gullies and draws because the mechanics of growth and change are clearer in those than in large valleys, but the same principles evidently control the development of all. The same factors must also control the extensive stripping of stratum plains.

Near Ferguson, in Blaine County, Okla., the peneplain on the Enid formation is exceptionally well developed. In the midst of this nearly flat plain the headwaters of Salt Creek flow in a flat-bottomed valley 40 feet deep and a considerable fraction of a mile wide. The edge of this valley, where crossed during the reconnaissance, is an abrupt escarpment marked by a very narrow strip of badlands but is straight for long distances and unbroken by any ravines within sight. If the escarpment is left out of view, here are two flat plains at different levels, one as flat as the other. A few hundred feet back from the top of the escarpment the peneplain is not being worn down by streams. At 200 feet out from its foot the lower plain is perfect. This lower plain is not a flood plain, nor is the escarpment an ordinary stream bluff. The stream has had nothing to do with making

either feature except to lower the local base-level. It would appear that the gradient of Salt Creek is very moderate for so small a stream. The surface is simply being stripped horizontally. The rock is fine argillaceous red sandstone or sandy shale. There is no reason to think that an alternation of resistant and weak beds is a significant factor. This is one of many striking illustrations of the tendency toward rapid lateral stripping with little or no evidence of wearing down. Examples were found throughout the outcrop of the Permian "Red Beds," though few exhibit such vigorous escarpment cutting. The two significant and remarkable things about Salt Creek are that a plain only 40 feet above its local base-level should be attacked so vigorously and that there should be such a lack of dendritic dissection.

An extreme illustration of the same process is found in the valley of the South Fork of Wichita River in Knox County, Tex., a few miles north of Benjamin. Here the river has cut a trench 8 miles wide in one of the flattest plains in the region. The walls of the trench are between 100 and 150 feet high, and the floor is almost flat. Small residual masses stand upon it, but the relief is in few places more than 10 feet and is of such a character as to show that the stream has never meandered over more than an insignificant fraction of the valley floor. The one thing that the stream has done is to lower the local base-level. The rest of the trench cutting was done by lateral stripping. The limiting walls, though notched in a small way, are surprisingly straight, and no tendency to dendritic dissection was seen in the adjacent flat upland.

Stratum plains.—The mention of "stripping" at once suggests the denudation of certain resistant beds and the production of stratum plains, which need not be at the local base-level. In the valleys thus far mentioned no positive evidence was seen that the levels of the new and lower plains (the valley floors) were thus determined. The topographic results may suggest resistant beds beneath the valley floors, but it should be remembered that similar stripping is observed in gullies and draws where the control of resistant beds can not be assumed, and that the general appearance of these larger valleys suggests that the streams are at their local base-levels, thus making unnecessary the hypothesis of resistant beds.

Advancing once more in the scale of size, we come to the broad plains which lie between the major eastward-facing escarpments. Here there is definite evidence in the escarpments themselves that the relative resistance to erosion of the beds has been an important factor in fixing the levels of the several plains, at least near their eastern edges. To some extent, at least, these plains conform in origin to the customary conception of a stratum plain.

Special conditions of valley cutting in scarped plains.—Another theoretical problem concerns the conditions of peneplanation and valley cutting peculiar to scarped plains (p. 116). The redevelopment of escarpments in a second cycle implies that certain more resistant beds have been able, at least in part, to maintain temporary base-levels for stream basins above the escarpments. It is conceivable that peneplains may be developed on the intervening weak beds before the master streams flowing over the strong beds have cut down their profiles completely to the new base-level. Further lowering of the stream's bed across the hard rocks must then be accompanied by a corresponding down cutting within the limits of the intervening peneplains. The rate of such down cutting may be so slow that the local peneplains are lowered concurrently. On the other hand, values may be assigned to the several factors involved (resistance of escarpment rock and of overlying beds, power of streams, area of basins, etc.) which make it possible for the streams to cut shallow valleys in the peneplains. The factors have not been evaluated in this area, but many of the streams, especially in the western part, occupy wide valleys of gentle slope, trenched by narrow valleys between steep bluffs. It seems probable that these wide valleys are due to the conditions here described, which attend the wearing down of scarped plains and do not indicate a distinct uplift of the region, as does, presumably, the more recent and abrupt intrenchment.

Aggrading streams.—It is frequently assumed that the characteristic features of the stream channels of this region indicate aggradation—that is, the progressive filling of the valleys with alluvium. The features referred to are the exceedingly wide, flat channels showing at low water numerous sand bars among which the stream flows in "braided" fashion so long as any water remains in the channels (Pl. XVIII, A). Without doubt such features are characteristic of "overloaded" streams. There can be no question that when the features visible at low water were formed the stream was supplied with more load than it could transport and was depositing more than it was removing. On the other hand, the major features of many of the valleys give no support to the assumption of progressive aggradation. They may even indicate the opposite. Terracing is common in the larger valleys. On the Prairie Dog Fork of Red River the 80-foot terrace seen in the background in Plate XVIII, A, consists of laminated alluvium, the upper 40 feet of which stands with a vertical face a few hundred yards from the river. Necessarily such a terrace is a short-lived feature, and it can not have been very long since the stream cut down to its present level and exposed its earlier alluvium to erosion. Yet no stream could be found which presents in a more typical form the features commonly interpreted as indicating aggradation.

The building of a sand bar is of course a more recent process than the cutting of a terrace, and it is not impossible that recent down cutting has given way to still more recent filling. Nothing is yet known, however, to invalidate the assumption that the aggradation noted is simply that which is incidental to the subsiding stages of every flood, and that during the rising stages of the floods more material is carried away than is deposited during the subsiding stages. The process of removal is of course not subject to direct observation, nor are its results except as seen in the larger features of the valley. The features due to periodic deposition are the ones that most appeal to the eye during 99 per cent of the time.

It follows from this that a so-called "overloaded" stream is not necessarily an aggrading stream in the sense that implies progressive or cumulative aggradation, but one which is supplied with a very large volume of detritus, some of which moves forward with each flood. Between such times the excess of load is stowed away, a part of it in sand bars but much the greater part of it in the thick sheet of sand and gravel that rests on the bedrock under the bed of the stream. If this sheet is so thick that the scour during floods fails to reach the rock beneath, then deposition has been cumulative and the stream has been aggrading, for the level of the bedrock surface is due to erosion.

As the possible depth of scour by such streams is not known, it can not be positively asserted that the scour always reaches the bedrock. The very few data obtained on the thickness of sand and gravel under channels seem to indicate that it is proportional to the size of the stream, and that this sheet of material, though thicker than would be casually assumed to be subject to scour, is not thick enough to warrant the positive conclusion that it is not subject to such removal. Depths to rock beneath the larger streams in this area seem to be fairly uniform—from 30 to 40 feet, or very little more. Under these circumstances much importance should be attached to the general features of the valley, as suggested above.

The additional fact that active gullying is in progress near the larger streams adds to the evidence that these streams are, on the whole, degrading their channels instead of aggrading. Too much weight should not be given to the evidence of gullies, however, in view of their intimate connection with vegetation, cultivation, grazing, etc. The distribution of active gullying has not been sufficiently studied to determine what the influence of these factors may be.

SUMMARY OF PHYSIOGRAPHIC FEATURES AND HISTORY.

Relief.—The region is in general one of slight relief, less than 100 feet in a mile on the average, and features showing relief of 200 feet

are exceptional. Large areas are so nearly flat that the slopes should be called faint rather than gentle. The coarse-textured drainage pattern is an additional characteristic of a peneplain.

The more striking features of the relief are eastward-facing escarpments and intrenched valleys. In the southwestern part of the region steep-sided mesas are also noteworthy.

Streams.—The region from Arkansas River on the north to Brazos River on the south is crossed by a number of remarkably parallel streams. Probably nowhere else in the United States do so many main streams run so near together for such long distances. Most of these streams are intrenched in relatively narrow valleys. They are characteristically but not universally attended, especially on their northeast banks, by belts of sand dunes from 2 to 10 miles or more wide (Pl. XVI, C, D).

Indications of more than one cycle of erosion.—Indications of at least two cycles of erosion are widespread, and an additional rejuvenation has also occurred in many places. The features suggesting two or more cycles are the intrenchment of all the larger valleys and many of the smaller ones and active gulying near some intrenched streams. All the main streams of the region were crossed in this investigation, most of them at more than one place. The Arkansas, Salt Fork of the Arkansas, Cimarron, North Canadian, Canadian, Washita, and the several forks of Red River and of the Wichita and Brazos are all intrenched below the peneplain level. Generally they are bordered by bluffs, more or less steep, the full height of which ranges from 50 to 200 feet. Where bluffs are lacking their place may be taken by long slopes. At many places, especially in the western part of the area, both bluffs and long slopes may be seen, the slopes rising for a mile or more from the top of the bluffs to the level of the upland. This is seen on most of the upper branches of the Red, Wichita, and Brazos. A revival of cutting power is, of course, indicated by the bluffs. Whether the old valleys indicated by the gentle slopes belong to the cycle of peneplanation or to a later cycle remains undetermined by any field study yet made. Considerations mentioned above under "Special conditions of valley cutting in scarped plains" show that these slopes do not necessarily indicate revival of crustal uplift.

From the study made in the field it was not possible to correlate peneplains for long distances. The two cycles observed at one place may or may not correspond to the two cycles observed elsewhere.

Hypotheses respecting former base-leveling.—To what extent the entire area should be conceived of as having been peneplaned in the commonly accepted sense of that term (reduced nearly to base-level) is uncertain. If the entire area ever was a single peneplain, the present escarpments must have been produced by revival, and the

several plain belts between them are either peneplains or stripped plains of a newer cycle.

Over against this conclusion may be set the hypothesis that the area was never one general peneplain and that the existing escarpments have been present, though retreating westward, throughout the process of denudation. It may be that in the general down cutting each escarpment-making member has determined a local base-level and that the plains west of it to the next escarpment were kept cut down to the local base-level by the ordinary processes of stream and inter-stream erosion. Again, it may be that these familiar processes were always subordinate, and that progressive lowering has been accomplished mainly by the westward recession of escarpments. The general straightness of the escarpments and, in a large way, the levelness of their tops favor the assumption of general peneplanation.

The remarkable parallelism of the streams requires the assumption of a very flat plain on which they originated. This may have been either a peneplain or the former eastward extension of the Tertiary mantle of the High Plains.

It seems probable, therefore, that there occurred in this region (1) the formation of a general peneplain, (2) one or more uplifts, and (3) the development of the present escarpments and intervening plains by renewed erosion in which lateral stripping as described above was prominent and perhaps dominant. This process would account for the typical steep-sided mesas found especially in the Texas part of the region. It would also explain the juxtaposition of other plains at diverse levels, which would otherwise require the assumption of distinct uplifts and partly completed cycles.

It is probably best to speak of these plains as peneplains rather than stratum plains. In any case they were developed by a combination of processes and probably at their local base-levels. Throughout much of the larger part of the area they now have the characteristic topography of what is commonly called a peneplain.

A.B.C

E.		Page.
Enid formation, features of, in Oklahoma-----	120-121	
Erosion, canyon cycle of-----	16-17	
chemical processes of-----	41-42	
early, in the Rocky Mountains, in Colorado-----	14	
mechanical processes of-----	39-41	
in arid climates-----	126-132	
third cycle of-----	2-3, 14	
two cycles of, recognized in the Rocky Mountains, in Colorado-----	1-2	
Escarments, receding, on gully, plate showing-----	122	
Estes Park, Colo., origin of-----	7, 14	
plate showing-----	7	
Exfoliation of rocks, features of-----	40-41	
F.		
Faulting in the Papago country, Ariz-----	33-36	
Felsite, erosion of-----	46	
Fillman, L., determination of roundness of limestone pebbles by-----	113-114	
Flatness ratio, formula for-----	93	
Flats, adobe, description of-----	69-70	
adobe, wind deposits on-----	71	
Flattop Mountain, Colo., plate showing-----	6	
view northwest from, plate showing-----	6	
Flattop peneplain, in Colorado, correlation of-----	14	
formation of-----	15	
modification of, by glaciers-----	13	
remnants of-----	3, 4	
plates showing-----	6, 7, 10	
Flood, sheet, description of-----	68-69	
Florissant, Colo., origin of gravel beds near-----	16	
Fossils, occurrence of, in the Papago country, Ariz-----	22, 23, 24, 31	
Fragments, separation of, from rocks-----	92	
Front Range, Colo., profile across, showing relation of Flattop peneplain to Rocky Mountain peneplain-----	5	
G.		
Georgetown, Colo., quadrangle, peneplain recognized in-----	1-2	
Gidley, J. W., fossils determined by-----	31, 32	
Gila River, drainage course to, from Barajita Valley-----	68	
terraces on-----	30-32, 71-73	
Girty, G. H., fossils determined by-----	22, 23	
Glaciation, pre-Wisconsin, apparent results of-----	12, 13	
Wisconsin, results of-----	13	
Glossary of physiographic terms-----	86-90	
Gneiss, closely jointed, erosion of-----	46	
Granite, erosion of, on mountain slopes-----	45-46	
niches formed in-----	49-50	
Gravel beds near Florissant, Colo., origin of-----	16	
Great Plains, location and altitude of-----	115	
Greer formation, topography on, in Oklahoma and Texas-----	123	
Gregory, H. E., on the discrimination of classes of pebbles-----	91	
Growler Mountains, Ariz., faults in-----	36	
from the west, plate showing-----	43	
Gullies, branching of, influences affecting-----	126-127	
in arid regions, features of-----	127	
in humid regions, features of-----	126-127	
on mountain slopes, formation and filling of-----	43-44	
<i>See also</i> Draws.		
H.		
Hagues Peak, glacier on, naming of-----	13	
glacier on, plate showing-----	7	
Hallett Glacier, Colo., features of-----	13	
plate showing-----	7	
Hallett Peak, Colo., plates showing-----	6, 7	
Headwater basin in the Sand Tank Mountains, Ariz-----	61	
High Plains section of the Great Plains, eastern escarpment of, in Texas, plate showing-----	120	
origin and features of-----	115-116	
I.		
Igneous rocks, accumulation of débris from-----	15	
Inscription painted on rock, persistence of-----	49-50	
J.		
Jackson Butte, Ariz., basalt of-----	27	
K.		
Kino, Father, description of Santa Cruz Valley by-----	78, 79	
Kirk, Edwin, fossils determined by-----	23	
L.		
Landslides, erosion by, in arid regions-----	128	
Lava, cliff slopes of, on the Ajo Mountains, Ariz., plates showing-----	42	
mountain capped with, in the Cabeza Prieta Mountains, plate showing-----	43	
Lavas, bedded, erosion of-----	43	
<i>See also</i> Volcanic rocks.		

	Page.		Page.
Little Ajo Mountains, Ariz., probable Mesozoic igneous rocks in.....	25	Papago country, Ariz., character of the mountains in.....	36-37
Longs Peak, Colo., plates showing.....	6, 12	former moist climate in.....	78-80
The Chasm on, origin of.....	13	geography of.....	19-20
plate showing.....	10	geologic history of.....	81-85
timber-line tree on, plate showing.....	11	geology of.....	20-37
		reconnaissance geologic map of.....	In pocket.
M.		stratigraphy of.....	20-33
McGee, W. J., cited.....	69	structure of.....	33-37
Maricopa Mountains, Ariz., east slope of, plate showing.....	61	Tertiary events in.....	82-83
felsite of outlier east of.....	27-28	Tertiary rocks in.....	26-28
Measurement of pebbles, method of.....	93-96	Patagonia Mountains, Ariz., Comanche rocks in.....	24
Medicine Bow Mountains, plate showing.....	6	Mesozoic igneous rocks in.....	25
Mesozoic rocks in the Papago country, Ariz.....	24-26	Pebbles, field work on, method of.....	106-109
Mills moraine, Colo., features of.....	9, 13	glacial, from Afton Junction, Iowa, plates showing.....	95
plate showing.....	9	glacial and sand-blasted, before and after artificial abrasion, plates showing.....	94
Monadnocks, examples of, on the Flattop peneplain in Colorado.....	15	measurements of, plotting of.....	97-102
Moraine Park, Colo., moraine south of, origin of.....	13	original shapes of.....	92-93
moraine south of, plate showing.....	7	relation of roundness of, to size and to distance of transportation.....	108-111
Mountain slopes, angles of, in the Papago country, Ariz.....	38, 42	Pediments, dissected, plates showing.....	60, 61
angles of, influences controlling.....	42-46	mountain, burying of.....	58-60
boulder-controlled, production and persistence of.....	43-46	coalescence of.....	60
cliffy, production and persistence of.....	42	dissection of.....	53, 60-65
conditions determining.....	38-39	formation of.....	48, 54-58
grades of.....	38, 42	nature of.....	52-54
plate showing.....	60	Peneplain east of the High Plains in Texas, features of.....	125
rain-washed, erosion of.....	46	Feneplain southwest of Alva, Okla., plate showing.....	120
Mud flows, development of scarps by, in arid regions.....	128	Pennsylvanian series, surface upon, in southeastern Kansas and northeastern Oklahoma.....	121
N.		Percolation of surface water, influence of, on the branching of gullies.....	127
Needles, The, Colo., plates showing.....	7, 12	Permian rocks, escarpment of, near Throckmorton, Tex.....	124-125
Niches, formation of.....	49-51	escarpments of, near Aspermont, Tex.....	125
Nogales Wash, Ariz., course of.....	74	Phyllite, erosion of.....	46
valley of.....	75	Pikes Peak, Colo., plateau near, features of.....	2
Nomographic charts, use of.....	96	Pillars, formation of.....	51-52
O.		"Plains Border," conclusions on.....	118
Oklahoma, western, physiographic features and history of.....	132-134	field work in.....	119-120
Osage section of the Central Lowland, features of.....	116-117	formations recognized in.....	120
P.		problem of.....	117-118
Paige, Sidney, cited.....	55	Plains, scarped, cutting of valleys in.....	131
Paleozoic rocks in the Papago country, Ariz., nature and age of.....	22-24	stratum, origin of.....	130
		"Platforms, subaerial." See Pediments.	
		Playas, occurrence of.....	70
		Potrero Creek, Ariz., course of.....	74

	Page.		Page.
Prairie Dog Fork of Red River, Hall County, Tex., plate showing-----	122	Santan Mountains, Ariz., volcanic rocks of-----	27
Pre-Cambrian basal complex in the Papago country, Ariz.-----	22-22	Sapping, erosion by, in arid regions-----	128
Prospect Mountain, view from, plate showing-----	7	Scale, circular logarithmic, description of-----	96
Q.		Schist, erosion of-----	46
Quartermaster formation, topography on, in Oklahoma and Texas-----	123	Shapes of pebbles, original-----	92-93
Quaternary deposits in the Papago country, Ariz.-----	28-33	Sierra del Pinacate, Ariz., lava flow from-----	33
R.		Sierra Estrella, Ariz., Mesozoic igneous rocks in-----	25
Recession of mountain slopes, process causing-----	42-46	Sierra type of mountain, process of carving-----	47-48
"Red Beds" hogback, plate showing-----	8	Sink holes west of Shamrock, Tex., plate showing-----	122
"Red Beds" of uncertain relation, topography on, in Oklahoma-----	123-124	Slopes of mountains. <i>See</i> Mountain slopes.	
Relief on Enid formation in Grant County, Okla., plate showing-----	122	Sonoita Creek, Ariz., course of-----	74
Relief on Greer formation in Dewey County, Okla., plate showing-----	122	Sonoita River, Ariz., cutting of channel of-----	79
Rigor, use of term-----	110	drainage course to, from Baboquivari River-----	67-68
Rio Puerco, N. Mex., cutting of channel of-----	80	Sprague Glacier, Colo., location of-----	13
Rivers. <i>See</i> Streams.		plate showing-----	6
Rock shelters, formation of-----	50	Stanton, T. W., fossils determined by-----	24
Rock spalls. <i>See</i> Boulders.		Stream, graded, use of term-----	47
Rocky Mountain peneplain, evidence of-----	5, 14	Streams, appearance of aggradation by, in arid regions-----	131-132
features of-----	2	axial, in arid valleys-----	67-68
formation of-----	15-16	tributary, in arid valleys-----	68-69
modification of, by glaciers-----	13	parallel, in Oklahoma and Texas-----	133
remnants of, plates showing-----	7, 12	Striae, removal of, from pebbles by abrasion-----	114
Rocky Mountains, profile across, through Longs Peak, events indicated by-----	3	Stripping of valleys and stratum plains-----	129-130
uplift of-----	14	Stylus for use with nomographic chart, construction of-----	96
Roundness ratio, formula for-----	93	T.	
Rupture of rocks, cause of-----	40	Tabosa Valley, Colo., features of-----	12, 14
Russell Fork of Big Sandy River, Va., course of-----	105	plate showing-----	12
quartzite on-----	105-106	Talus, formation and removal of-----	43-46
S.		Taylor Glacier, Colo., location of-----	13
Sacaton Mountains, Ariz., Mesozoic igneous rocks in-----	25	Temperature of rocks, changes in-----	39-41
Sand Tank Mountains, Ariz., faults in-----	84-85	Terraces, formation of, in the Papago country, Ariz.-----	71-81
headwater basin and dissected pediment in, plate showing-----	61	Texas, northern, physiographic features and history of-----	132-134
Santa Cruz River, Ariz., course and tributaries of-----	74-75	Thompson River canyon, Colo., plates showing-----	7, 8
terraces along-----	75-78	Throckmorton, Tex., escarpment near-----	124-125
Santa Rita Mountains, Ariz., Comanche rocks in-----	24	Tucson, Ariz., former conditions near-----	78
Mesozoic igneous rocks in-----	25	Santa Cruz Valley near-----	77, 78
		Tucson Mountains, Ariz., volcanic rocks of-----	27
		Tuff, erosion of-----	43, 46
		Tule Mountains, Ariz., faults in-----	35-36
		Tule Tank, Ariz., pass west of-----	60
		Tumacacori Mountains, Ariz., Mesozoic rocks in-----	24
		Tumamoc Hills, Ariz., volcanic rocks of-----	27

	Page.		Page.
Tumbling barrel for abrasion of pebbles, plates showing--	95	Volcanic rocks, distribution of, in the Papago country, Ariz-----	26-28
use of-----	110	W.	
Tyndall Glacier, Colo., gorge below, features of-----	8, 13	Weathering, action of temperature in-----	39-41
gorge below, plate showing----	8	Whitehorse sandstone member, topographic features formed by, in Oklahoma---	122-123
location of-----	13	Wind, action of, on trees and snow--	11
plate showing-----	8	deposits made by, in the Papago country, Ariz-----	70-71
V.		influence of, in checking gully-ing-----	127-128
Valley, rejuvenated, plate showing--	126	Woodward formation, topographic features on, in Oklahoma-----	122-123
Valleys, changes taking place in---	66		
drainage of-----	66-69		
origin of-----	65-66		
stripping of, in arid regions--	129-130		
Vekol Valley, Ariz., terraces and stream channels in---	80-81		

DEPARTMENT OF THE INTERIOR

ALBERT B. FALL, Secretary

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, Director

Bulletin 730

**CONTRIBUTIONS TO THE GEOGRAPHY
OF THE UNITED STATES**

1922

MARIUS R. CAMPBELL

GEOLOGIST IN CHARGE



WASHINGTON

GOVERNMENT PRINTING OFFICE

1922

CONTENTS.

[The letters in parentheses preceding the titles are those used to designate the chapters for advance publication.]

	Page.
(A) Peneplains of the Front Range and Rocky Mountain National Park, Colo., by W. T. Lee (published Apr. 4, 1922)-----	1
(B) Erosion and sedimentation in the Papago country, Ariz., with a sketch of the geology, by Kirk Bryan (published June 8, 1922)---	19
(C) A method of measuring and plotting the shapes of pebbles, by C. K. Wentworth (published June 26, 1922)-----	91
(C) A field study of the shapes of river pebbles, by C. K. Wentworth (published June 26, 1922)-----	103
(D) Physiographic provinces and sections in western Oklahoma and adjacent parts of Texas, by N. M. Fenneman (published December 20, 1922)-----	115
Index -----	135

ILLUSTRATIONS.

	Page.
PLATE I. Map and profile section of a part of the Central City quadrangle, Colo.-----	2
II. A, Flattop Mountain, Colo., the type area of the Flattop peneplain; B, General view northwestward from Flattop Mountain-----	6
III. A, The Continental Divide, Colo.; B, Hallett Glacier, Colo.; C, Estes Park, Colo.-----	7
IV. A, Thompson Canyon, Colo.; B, Gorge below Tyndall Glacier, Colo.-----	8
V. A, Andrews Glacier, Colo.; B, Mills moraine, Colo.-----	9
VI. A, The Chasm, Longs Peak, Colo.; B, Cirque near Comanche Peak, Colo.-----	10
VII. A, Moraine south of Copeland Lake, Colo.; B, A timber-line tree on Longs Peak, Colo.-----	11
VIII. A, Black Canyon and The Needles, Colo.; B, Longs Peak and Tahosa Valley, Colo.-----	12
IX. Reconnaissance geologic map of the Papago country, Ariz. In pocket.	
X. A, Ajo Peaks, Ariz., from the east; B, Clifty slopes of massive lava flows on the west side of the Ajo Mountains, Ariz.-----	42

	Page.
PLATE XI. A, Growler Mountains south of Bates Well, Ariz., from the west; B, Lava-capped mountain in the Cabeza Prieta Mountains, Ariz., from the west-----	43
XII. A, Pass west of Tule Tank, Ariz.; B, Mountain slope and dissected pediment-----	60
XIII. A, Headwater basin and dissected pediment in the Sand Tank Mountains, Ariz.; B, East slope of Maricopa Mountains, Ariz-----	61
XIV. A, Convexity gage; B, Glacial and sand-blasted pebbles before artificial abrasion; C, Glacial and sand-blasted pebbles modified by artificial abrasion-----	94
XV. A, Striated glacial pebbles from Afton Junction, Iowa; B, Glacial pebbles from Afton Junction, Iowa; C, Tumbling barrel in which experimental studies of abrasion of pebbles are made-----	95
XVI. A, Eastern escarpment of the High Plains, Hall County, Tex.; B, Peneplain on Enid formation southwest of Alva, Okla.; C, Sand dunes near Cimarron River, Woods County, Okla.; D, Fixed dunes near Cimarron River, Woods County, Okla-----	120
XVII. A, Relief on stronger sandstones of Enid formation near a larger valley, western border of Grant County, Okla.; B, Relief on Greer formation near a larger valley, northern border of Dewey County, Okla.; C, Sink holes in Gypsum escarpment, 4 miles west of Shamrock, Wheeler County, Tex-----	122
XVIII. A, Prairie Dog Fork of Red River, Hall County, Tex.; B, Gully with receding escarpments, Grant County, Okla.; C, Old valley rejuvenated, north of Chickasha, Okla-----	126
FIGURE 1. East-west profile across the Rocky Mountains through Longs Peak and Grand Lake, Colo-----	3
2. Profile across the Front Range through Flattop Mountain from Grand River to The Crags, Colo-----	5
3. Profile from the crest of the mountains at Hagues Peak north-eastward to the Great Plains in northern Colorado-----	16
4. Geologic cross sections in the western part of the Sand Tank Mountains, Ariz-----	34
5. Geologic cross section in the Tule Mountains, Ariz-----	35
6. Geologic cross section of the southern part of the Lechuguilla Desert, Ariz-----	35
7. Diagram to show the range of mountain slopes-----	42
8. Sketch map of the Papago country, Ariz., showing distribution, so far as observed, of gullied and ungullied mountains of approximately the same size-----	44
9. Diagram showing three stages in the erosion of a block of the earth's crust to form the sierra type of mountain-----	47
10. Cross section of niche in granite at Tinajas Altas, Ariz-----	49
11. Diagram illustrating weathering of Tertiary arkose conglomerate in the Papago Saguaro National Monument, Ariz-----	50
12. Cross section of a niche in coarse conglomerate, Papago Saguaro National Monument, Ariz-----	51
13. Map of part of the Sacaton Mountains, Ariz-----	52
14. Map of the northern border of the Baboquivari Mountains, Ariz-----	53

	Page.
FIGURE 15. Diagram showing the structural relations resulting from the slow but continuous filling of a structural basin.....	56
16. Diagram showing the structural relations resulting from the rapid and continuous filling of a structural basin.....	58
17. Diagram showing the structural relations resulting from the discontinuous filling of a structural basin.....	59
18. Sketch map of the northwestern part of the Sand Tank Mountains, Ariz., showing location of dissected and concealed pediments.....	60
19. Map of the vicinity of Fresno and Topahua, Ariz., showing dissected pediment.....	62
20. Diagram showing the structural relations assumed for a typical valley in the Papago country, Ariz.....	63
21. Cross sections on the north and west sides of the Baboquivari Mountains, Ariz.....	64
22. Cross section of part of Santa Cruz Valley (Nogales Wash), Ariz., from Mount Benedict to the Tumacacori Mountains.....	74
23. Cross section of Santa Cruz Valley from Sardina Peak to the Santa Rita Mountains near Tubac, Ariz.....	75
24. Cross section of Santa Cruz Valley at Jaynes, Ariz.....	75
25. Cross section of Santa Cruz Valley near Toltec, Ariz.....	76
26. Profiles and table showing shapes of pebbles.....	94
27. Convexity gage.....	94
28. Modified convexity gage.....	95
29. Profile from which block dd in figure 28 was constructed.....	95
30. Circular logarithmic scale.....	96
31. Stylus for use with nomographic chart.....	96
32. Chart showing characteristic positions of different types of pebbles.....	98
33. Axial line of migration in shape of a river pebble.....	99
34. Graph showing modification in shape of five glacial pebbles that were subjected to abrasion in a tumbling mill.....	100
35. Graph showing modification in shape of five sand-blasted pebbles that were subjected to abrasion in a tumbling mill.....	101
36. Sketch map of vicinity of Russell Fork of Big Sandy River, Va.....	104
37. Profile of the upper course of Russell Fork of Big Sandy River, Va.....	105
38. Chart showing distribution according to shape of 642 river pebbles, cobbles, and boulders from Russell Fork of Big Sandy River, Va.....	107
39. Curves showing relation of roundness of pebbles to distance of transportation.....	108
40. Curves showing relation of roundness ratios to size of pebbles.....	109
41. Final curve of rounding of pebbles with respect to distance traveled.....	110
42. Comparison of curves of rounding of pebbles with respect to distance traveled, obtained by field and experimental measurements.....	111
43. Index map of western Oklahoma and adjacent parts of Texas.....	117
44. Physiographic sections in western Oklahoma and adjacent parts of Texas as revised.....	119

Bulletin 730a
BORROWER'S

DATE DUE

BORROWER'S NAME

[illegible]



3 2044 102 940 673